VIBSYS: Integrated Didactic and Research Platform for Vibration Analysis

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Abstract— **The paper introduces a new system for vibration acquisition and analysis for rotating machinery - VIBSYS. It includes a mechanical structure, data acquisition subsystem and a software system developed as a virtual instrumentation project. The latter implements the configuration of the data acquisition, signal processing steps and provides the user with an intuitive and easy to operate user interface. The main goal of the proposed approach is to enable bearing defect detection as an initial step in a complete procedure of predictive maintenance. Experimental results, based on a comparative study on two bearing types using envelope analysis techniques are also discussed. The platform plays a dual role as a didactic and research stand through its modular and scalable structure as well as versatility.**

***Index Terms*—vibration measurement, signal processing, fault detection, educational platform.**

I. INTRODUCTION

LARGE and small scale machinery employ a vast range of interconnected mechanical components which are prone to damage over time due to significant stresses in the course of operation. This introduces significant risk for the plant operator in the form of declined output over time or even lost production from unexcepted and costly machine malfunctions. Intelligent fault detection systems which are able to for specific machinery have recently been adopted by the industry stemming from a rich background of theoretical and applied research work over the last two decades [1].

Specific challenges in building such products lay in adequate component selection, implementation of appropiate processing strategies, which offer broad applicability with good detection, diagnosis and prediction results, system testing and validation. Remote and automated condition monitoring systems reduce the need for costly human periodic on-site intervention and by centralizing data in a single point, predictive maintenance for individual subsytems can be achieved.

The Vibration Analysis System (VIBSYS) emerged from a need to introduce students to modern concepts in machine condition monitoring as well as to offer a support platform for the validation of new research results. Didactic topics which can be approached using this kind of platform cover a wide area, at the intersection of mechanical and electrical engineering, which includes: transducer static and dynamic characteristics, fundamentals of data acquistion systems, distributed measurement systems, signal processing, digital filter design, and virtual instrumentation development.

An example is the usage of integrated electronics piezoelectric (IEPE) accelerometers. These merge piezoelectric sensitive elements for vibration measurement with local integrated circuitry for better response and sensitivity. The core functionality of the integrated electronics is to convert the high impedance charge signal into a low impedance voltage output which can be reliably transmitted over connexion cables. Another particularity is the usage of a networked data acquisition with high resolution and sampling rate analog input channels, which is easily integrated with field and enterprise device and computer networks.

Main contribution of this work is to present the design, structure and initial evaluation of the VIBSYS system, developed as a teaching and research support tool for the activities of the laboratory for Intelligent Measurement Technologies and Transducers (iMTT). As proof-of-concept and validation, envelope analysis, which is a combined time/frequency approach for fault detection, was implemented. We are able thus to correctly discern between working and used bearings.

The rest of the paper is structured as follows. Section 2 discusses recent related work in the field, concerned with the specific goal of underlining the novel nature of our work. The conceptual and applied system design is introduced in section 3. The functional diagram and component selection and integration details are presented. Section 4 is dedicated to briefly specifying the signal processing flow and includes the early experimental results for two bearing categories. Section 5 concludes the paper and lists envisioned directions for development.

II. RELATED WORK

A classification of common bearing defects is listed in [2]. They cover outer rim, lubrication, inner rim, rolling elements, ring irregularities, excessive friction, etc. Practical advice and numerically valid parameters for roll bearing fault detection are also suggested. An important element to consider is that by using a single accelerometer, the detection capabilities of the ensemble are limited to around 30%. Subsequent iterations will include a second, horizontal mounted transducer in order to increase the detection rate to over 90%. In [3], the authors use wavelet packet decomposition (WPD)

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together with support vector machines (SVM) for intelligent condition-based maintenance. The approach is applied to idler faults in belt conveyor systems for coal transportation and it achieves a success rate for predefined fault classes of 91.76%. The computation effort needed for implementation is at the limit for on-line monitoring, given the belt speed and available resources.

Self-powered vibration monitoring and fault detection systems are introduced in [4]. The relevant idea is to build an autonomous embedded device which can harvest energy directly from the investigated phenomenon, vibration in this case, perform local data processing and wirelessly relay high level information to a central collection point. The basic frequency based algorithms are used to detect thermal engine operating modes and transitions among them with good performance.

The company SpectraQuest Inc. is an established name in the field of vibration training equipment. The range of Machine Fault Simulators (MFS) [5] is offered in several versions according to complexity and specific components to be investigated such as: bearings, shafts, couplings and/or gearboxes. We argue that VIBSYS can become a suitable alternative to MFS due to its open hardware and software approach which allows users to actively get involved in the development of the simulator.

III. SYSTEM DESIGN AND COMPONENT SELECTION

The VIBSYS schematic diagram is introduced in Figure 1. An electric motor (ME) drives a rotating shaft thorugh an elastic coupling (CPL). The shaft is fitted at both ends with roll bearings (RL1, RL2) and a unbalancing flywheel (VL) in the middle, which can be fitted with varying size and weight parts. Motor speed control is achieved via a static frequency converter (CSF). Two IEPE acceleration transducers (VIB1, VIB2) are mounted on the vertical axis of the bearing enclosures and are connected to the data acquisition subsystem. An optical rotation sensor (TAH) is also provided. It bounces a ray of light off a reflecting applied to the flywheel, counting the speed of the shaft at the rate of 1 impluse/rotation. The three signals are interfaced to a data acquisition module on an Ethernet carrier, controlled via PC [6], which also runs the acquisition, processing and visualization client.

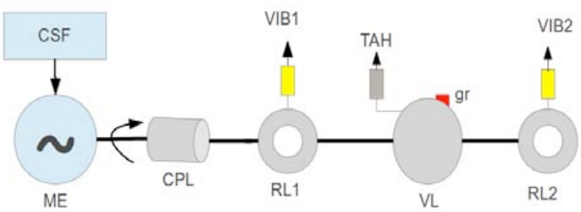

Fig. 1. Functional Diagram

A more detailed illustration of the system design is given in Figure 2. The following components have been integrated:

- Static frequency converter: Siemens Sinamics G110 series;
- Electric motor: Siemens 1LA9060-2KA60 0.18 kW, 3000 rpm syncron rotation;
- Accelerometer: Siemens VIB-Sensor S01 50g, 100 mV/g, 0.002 g resolution, 10 – 14 V bias output;
- Rotation sensor: Siemens diffuse optical sensor, 25 – 100 mm detection range;
- Data acquisition subsystem: National Instruments CompactDAQ Ethernet 9181 single slot carrier and National Instruments NI 9232 3 ch. analog input module, 24 bit, 104 kS/s;
- Mechanical parts: bearings NSK and CMB deep groove ball bearings, type 6004: D= 42 cm, d = 20 cm, w = 12 cm, elastic coupling.

Fig. 2. Component Illustration

Figure 3 shows the actual laboratory set-up during the experiments.

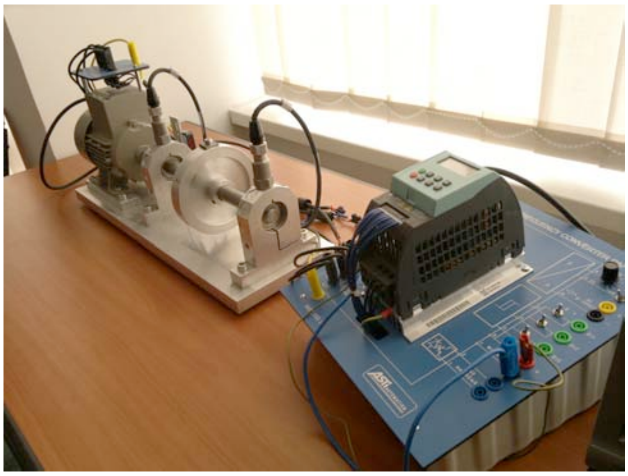

Fig. 3. Actual Laboratory Implementation

IV. ENVELOPE ANALYSIS FOR FAULT DETECTION

Four characteristic frequencies are defined for which bearing defects can take place in the bearings. These depend on the bearing geometry, as well as on the ball number, cage and ball diameter and also on the axis rotation frequency. The frequencies are defined by the equations:

$$F_C = \frac{1}{2} F_S \left(1 - \frac{D_b \cos(\phi)}{D_c}\right) \tag{1}$$

$$F_{BPI} = \frac{N}{2} F_S \left(1 + \frac{D_b \cos(\phi)}{D_c}\right) \tag{2}$$

$$F_C = \frac{N}{2} F_S \left(1 - \frac{D_b \cos(\phi)}{D_c}\right) \tag{3}$$

$$F_B = \frac{D_c}{2D_b} F_S \left(1 - \frac{D_b^2 \cos^2(\phi)}{D_c^2}\right) \tag{4}$$

The purpose of envelope analysis is to identify the characteristic bearing frequencies listed above on the spectrum of the envelope of the measured and filtered signal, leading thus to the diagnosis of its defects. Obtaining the repetition rate of a defect, we can infer upon its location, e.g. in the inner rim, outer rim or in the ball. The procedure for envelope analysis is given by Randall [1] (Figure 4). It is a combined time/frequency approach consisting of the following steps. The spectrum of the filtered signal is computed, from which an optimal frequency range is extracted [f1 f2], for example from the spectral excess. This result is shifted to the frequency range [0 (f2-f1)], where a doubling of the analyzed range takes place by introducing additional zeros. The range doubling is motivated by the analysis of the square of the envelope, which in turn doubles the frequency content of the signal. In the same time, we assure that the equivalent time-domain signal is analytic, having unilateral spectrum. By applying the inverse Fourier transform, the resulting signal is analytic and by multiplying with the complex conjugate the square of its envelope will be obtained. Subsequently the spectrum of the envelope square will be determined, which will contain the repetition frequencies.

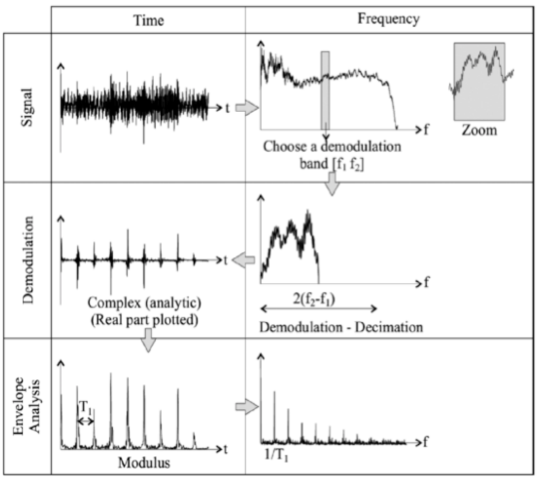

Fig. 4. Envelope Analysis Implementation [1]

For experimental validation, a complex virtual instrumentation project was developed, Envelope Examination System (ELEOS). It implements the above described procedures as well as offering users a high level degree of configuration regarding acquisition, filtering, band selection and demodulation. The user interface is shown in Figure 5 where one can observe the characteristic frequencies of the bearing defect based on its geometry and rotation speed, as well as the central area. The application employs a queued state machine design pattern with two parallel *while* loops. The first one is responsible for capturing events on the front panel, with the second one being responsible for executing the actions from the indicated states by the first loop. The tab control includes the windows: data acquisition, order analysis, linear prediction, MED, SK, envelope analysis. Communication is assured through a waiting queue, so that no event is lost in case of conflict and the processor is used only during state execution. Scalability is provided by retaining the states in a *typedef enum* structure.

Fig. 5. ELEOS Virtual Instrumentation Project for Envelope Analysis

Data acquisition was performed at a 25.6 KHz sampling frequency, as suggested in [2], the range 0-12.8 KHz, being enough for the detection of any possible defect. The measurements were performed in the range of 10-26 Hz, with an incremental 1 Hz step, corresponding to a motor rotation speed between 600 and 1560 rpm. The subsequent results are obtained for a 1200 rpm/ 20 Hz rotation speed. For a better comparative analysis on the envelope procedure, two sets of bearing were used: a new one from NSK and a used one from CMB. Chronological, the good bearings were tested first with the used ones afterwards. Figure 6 present the raw time series acquired from the new working bearings.

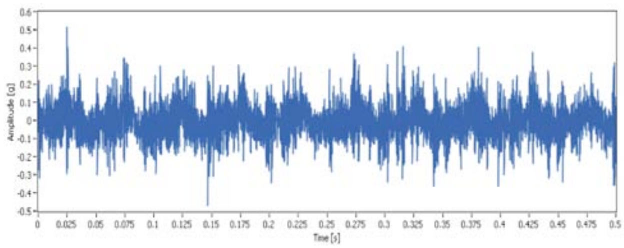

Fig. 6. Raw Time-domain Signal

For the center frequency fc = 9500 Hz and 2000 Hz range, the envelope in Figure 7 with its spectrum illustrated in Figure 8. One can observe the fundamental frequency at 76.8 Hz, and its visible harmonics at 153.6 Hz, 230.4 Hz, 306.9 Hz. This time, the fundamental frequency is very close to the characteristic defect frequency of the outer rim, so that we can localize the defect. Compared to the frequency derived from the bearing geometry, a difference of around 1% is observed. The approach thus gives good results even if, when the amplitude of vibration, as is the case with good bearings, the spectrum of the envelope can sometimes provide misleading information.

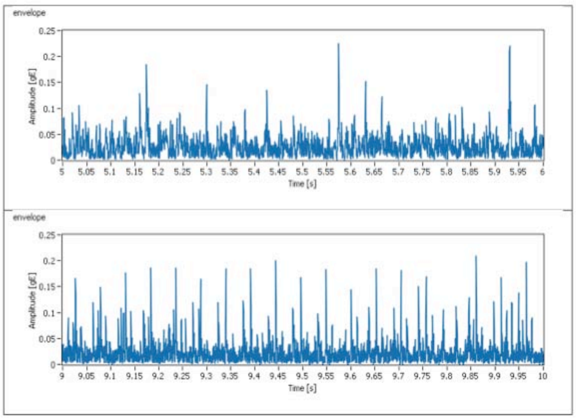

Fig. 7. Working vs. Used Bearing Envelope

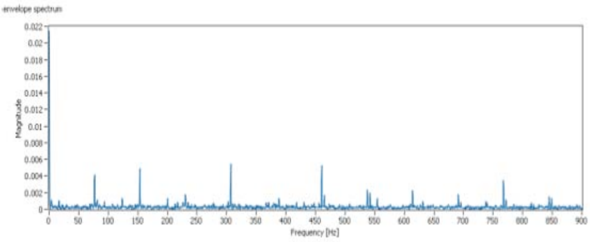

Fig. 8. Envelope Spectrum for the Used Bearing

A simplified defect stage indicator [2], involves also computing the enveloped spectrum, from where the diagnosis information also stems. If there is a defect, the envelope spectrum should show peaks over the spectral average. Peaks above 10% over the average indicate a serious defect, the ones over 5% indicate a mature defect while the peaks over 1% signal an incipient defect. The standard ISO 10816-1 [7] specifies reccomended limits for vibration variation limits, corresponding to rotating machinery, applicable for machines up to 15 kW. The classification ranges from A – good, 0.28-0.71 mm/s RMS, up to D – not permisibile, above 7.1 mm/s RMS.

There are some issues which have to be revised before the system can be fully validated:

- The limited samples analyzed imply that the dataset should be segmented and the results for each segment should be optimally composed. For practical reasons which have to do with the time allocated to data processing, a set of 256000 samples was analyzed, corresponding to a shaft rotation frequency of 20 Hz and a sampling frequency of 25.6 KHz of a number of 2000 full shaft rotations;
- In the case of multiple defects the diagnosis using envelope analyisis scales nonlinearly, becoming very challenging;
- Due to the specified dynamic range of the accelerometers, the measurements become distorted at 99 dB;
- A very useful approach would be testing the proposed method on known and localised defect bearings, obtaining a clear idea of the spectrum of a certain class of defects;
- Flywheel unbalance should also be compensated in order to perform measurements at equilibrium.

V. Conclusion

The relevance of the work is underlined by its practical implementation and by establishing a base for subsequent developments in the area of vibration analysis. Defect detection is a preliminary but essential stage in machine condition monitoring

Future work directions are targeted at enhancing the mechanical structure with the addition of horizontal placed accelerometers for better insight in the bearing functioning. Also the authors envision the replacement of the current PC-based approach and introducing a FPGA implementation on a real-time computing platform which will allow for increased complexity of the algorithms while maintaining the on-line behaviour.

Computational intelligence methods have the potential to round off the research for a full machine condition monitoring system. These include [8]: neural networks, bayesian networks, gaussian mixture models (GMM), hidden markov models (HMM), fuzzy reasoning, rough sets and genetic algorithms. All the methods lead to a natural continuation of the research from classic analysis and are open to advancing knowledge in predictive maintenance.

Acknowledgment

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