A PC-Based Vibration Analyzer for Condition Monitoring of Process Machinery

Saleem A. Ansari and Rauf Baig

Abstract— A fast-response PC-based vibration analyzer has been developed for fault detection and preventive maintenance of process machinery. The analyzer acquires multiple vibration signals with high resolution, and computes frequency spectra, root mean square amplitude, and other peak parameters of interest. Fast execution speed has been achieved by performing data acquisition and frequency spectrum computation using C-language. Vibration signals up to 10 kHz can be analyzed by the spectrum analyzer. Special algorithms, such as window smoothing, digital filtering, data archiving and graphic display have also been incorporated. With these features the vibration analyzer can perform most of the functions available in complex, stand-alone machines. The software for the analyzer is menu driven and user-friendly. The personal computer used is a 66 MHz PC-486 compatible machine. The use of a general purpose PC and standard programming language makes the vibration analyzer simple, economical, and adaptable to a variety of problems. The applications of the system in malfunction detection in rotating machinery are also described.

Index Terms— Data acquisition, digital filtering, fast Fourier transform, fault detection in machinery, PC-based vibration analyzer, VIBRATION.

I. INTRODUCTION

THE APPLICATION of vibration measuring and analyzing techniques for the fault diagnosis and preventive maintenance of plant machinery and components is well established [1], [2]. In particular, vibration monitoring of critical reactor components is significant both from safety and cost economics point-of-view in nuclear reactors [3].

Conventional vibration analyzers used for vibration monitoring in industry are complex and cost intensive. With the advent of personal computers as fast and cost effective machines for data acquisition and processing of multiple signals, these computers have received wide acceptance in industrial and reactor applications. The vibration analyzer based on a PC has several attractive features. It is simple, inexpensive, easy-to-repair, and is suitable for field applications. Since the computer programs are developed on the PC in standard programming languages, the vibration analyzer can be tailored to most of the customer's requirements. This paper describes the methodology and applications of the PC-based vibration analyzer. The development work was performed under a

research contract from International Atomic Energy Agency (IAEA).

A. Fault Detection in Machinery by Vibration Analysis

Vibration in rotating machinery has two definite identifying characteristics. These are vibration frequency and vibration amplitude. The principal component of the vibration frequency, usually, has the same value as the machine rpm. The vibration amplitude can be measured in three different ways; displacement, velocity, and acceleration. An increase in vibration amplitude almost always indicates some mechanical fault. Operation criteria representing vibration boundary levels for satisfactory and unsatisfactory running conditions depends upon the type of machine. The most widely adopted criterion for estimating machine status are those of Rathbone, Yates, and VDI 2056 [4], [5].

Once a machine problem is detected by an increase in vibration amplitude, the frequency spectrum analysis of the vibration signal is used for identification of the particular malfunction. Machine problems, such as unbalance, misalignment, defective bearings and gears can be identified by noting the dominant frequencies of vibration and their harmonics in the vibration spectrum.

II. PERSONAL COMPUTER-BASED VIBRATION ANALYZER

The development work for the PC-based vibration analyzer can be categorized as follows.

1) Selection of proper vibration transducers based on the criteria of high frequency bandwidth, better sensitivity and ease in handling.
2) Proper signal conditioning; amplification, filtering, and conditioning of the transducers signals, prior to interfacing with the computer
3) Analog-to-digital conversion of high frequency vibration signals.
4) Computation of frequency spectra of vibration signals. Evaluation of machinery status by analysis of vibration spectra.

In the PC-based vibration analyzer, multiple vibration signals are acquired in real-time with the help of fast, high-resolution data acquisition system. The data processing routines transform the digital time-domain data into frequency domain by using fast Fourier transform (FFT), and calculate signal auto- and cross-power spectral density functions and root mean square (rms) amplitude.
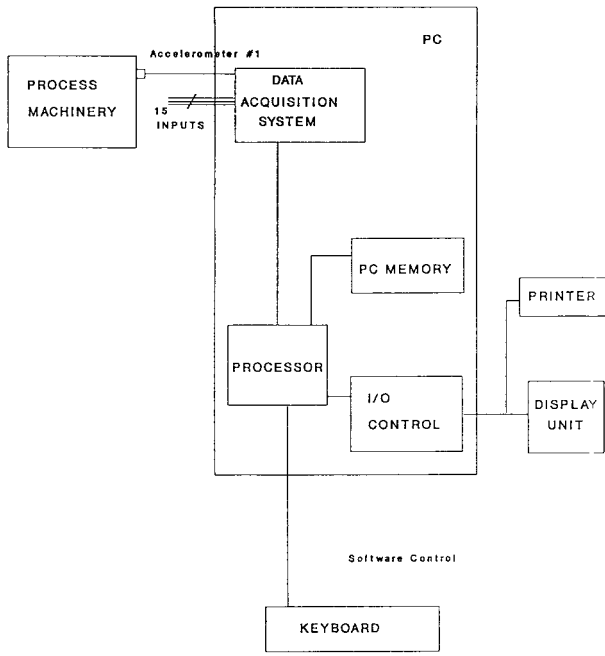
Fig. 1.   Block diagram of the PC-based vibration analyzer.

The rms value of acceleration of vibration, g, obtained by the power spectral density computation is converted into the unit of displacement, mils, using the formula

$$g = 0.0511 \times f^2 \times x \qquad (1)$$

where f is the frequency in hertz and x is the peak-to-peak displacement in inches.

The frequency spectra, or vibration "signatures," obtained by the computer are analyzed for machinery fault detection and identification using appropriate vibration criteria, as discussed earlier. In the first stage of the development work, the malfunction diagnosis is done by the program supervisor. A data base for probable causes of malfunctions in different types of machines depending on the machine rpm and load has been collected, based on actual experience as well as from the literature [8], [9]. In the second stage this data base is being installed on the computer. In this way the computer will be able to monitor automatically the status of rotating machinery, generate "alert" and "action" level alarms in case of abnormal behavior, and print probable cause of malfunction.

The block diagram of the PC-based vibration analyzer is shown in Fig. 1. Following is a description of its main functions.

A. Vibration Detection

Vibration accelerometers were used for converting mechanical vibration signals into electrical signals. The specifications of these transducers are [10]

measuring range:	-75 to 75 g;
sensitivity:	100 mV/g, at 100 Hz;
frequency bandwidth:	up to 10 kHz.

B. Data Acquisition

The requirements of the data acquisition system employed for vibration monitoring are fast conversion speed (high sampling frequency), high signal resolution, and multi-input capability. To incorporate these features a 16-input, 12-bit resolution analog-to-digital (ADC) card was selected for data acquisition with the following specifications [11].

analog inputs:	16 single ended, or eight differential;
digital inputs:	64;
ADC resolution:	12;
maximum over-voltage:	30 V;
digital outputs:	16;
analog outputs:	2 ($\square$10 V).

The analog input signals may have voltage values ranging switch selectable voltage ranges from ±0.5 V to ±10 V. Interrupt-based control provides simultaneous background data acquisition and foreground processing operation. The card also contains two digital-to-analog converters (DAC's) for analog display of the processed data.

C. Software Control

A computer code VIBRATION was developed for the control of data acquisition, signal processing, and graphic display. Since the range of frequencies of interest in vibration signals is of the order of several tens of thousands of Hertz, the execution time for the entire data acquisition and analysis cycle must be kept very short. This has been achieved with the help of fast executing algorithms and computer programs in C-language, which make it possible to obtain a maximum sampling frequency of the order of 20 kHz.

D. Data Processing

The flow chart of the computer code VIBRATION is shown in Fig. 2. As the first step in data processing, the digitized data (ADC levels) is transformed into engineering units (vibration acceleration, velocity or displacement). The following algorithms perform further data processing and spectrum analysis of the digitized data.

1) Window Smoothing: For smoothing of raw signal data, the Hanning (or raised cosine) window function was selected due to its better performance in dealing with the truncated data [12]. The Hanning window has the mathematical form

$$w_j = 0.5 \times [1 - \cos(2\pi j/(N-1))] \qquad (j = 0 \cdots N-1) \quad (2)$$

where N is the total number of samples in a single record. The basic function of window smoothing algorithm is to multiply the signal data in time domain with the window function of (2), which is equivalent to convoluting the spectrum of the signal with the spectrum of the window. In this way the Fourier transform components of the signal at high frequencies are eliminated, thus reducing the noise introduced by the signal truncation for finite record length signals.
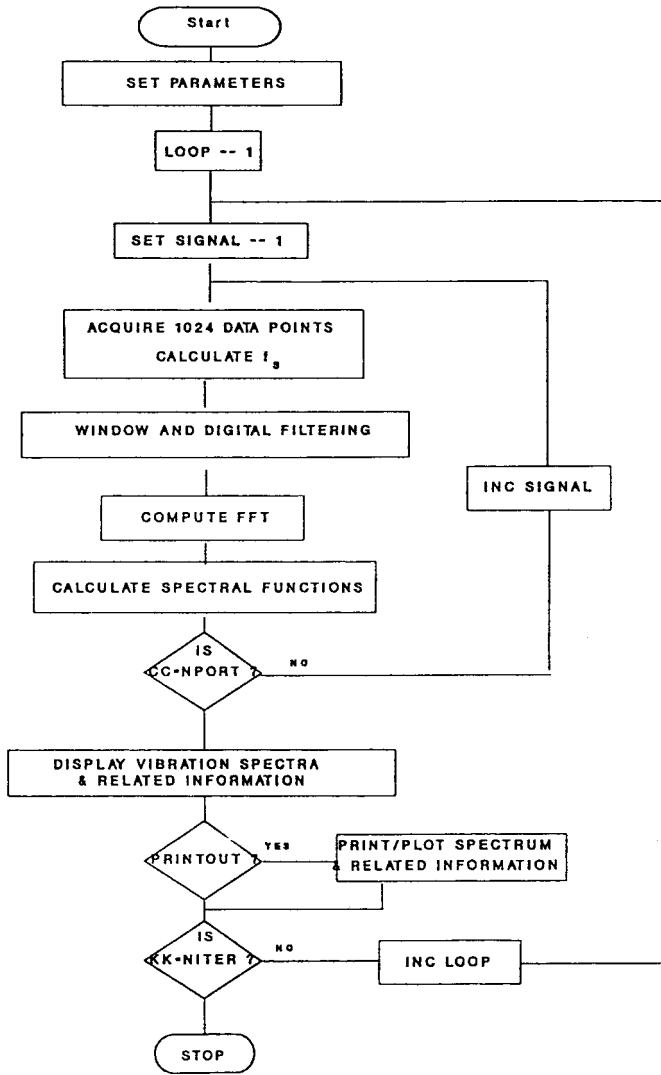
Fig. 2. Flowchart of the computer code "VIBRATION."

Fig. 3. Comparison of frequency response of electronic and digital filters.

2) Digital Filtering: Another feature of the data processing algorithm is digital frequency filtering of the time domain data. Digital filters, or filters implemented in software, have several attractive advantages over analog filters [13], [14], such as, no temperature drift, no component tolerance, and wide frequency range.

A second order, unity gain, low-pass Butterworth digital filter has been implemented in software [15]. The normalized transfer function of such an analog filter is given by

$$H_{(s)} = \frac{1}{s^2 + 1.414s + 1} \tag{3}$$

where s is the Laplace transform operator.

The digital filter algorithm reads the unfiltered digital data array (x) from the sample record and fills a new array (y), which contains the low-pass filtered data. The digital filter cutoff frequency is selectable by the operator.

The performance of the low-pass digital filter designed for the vibration analyzer was compared with an electronic active filter with 48 dB/octave frequency cutoff. White noise signal
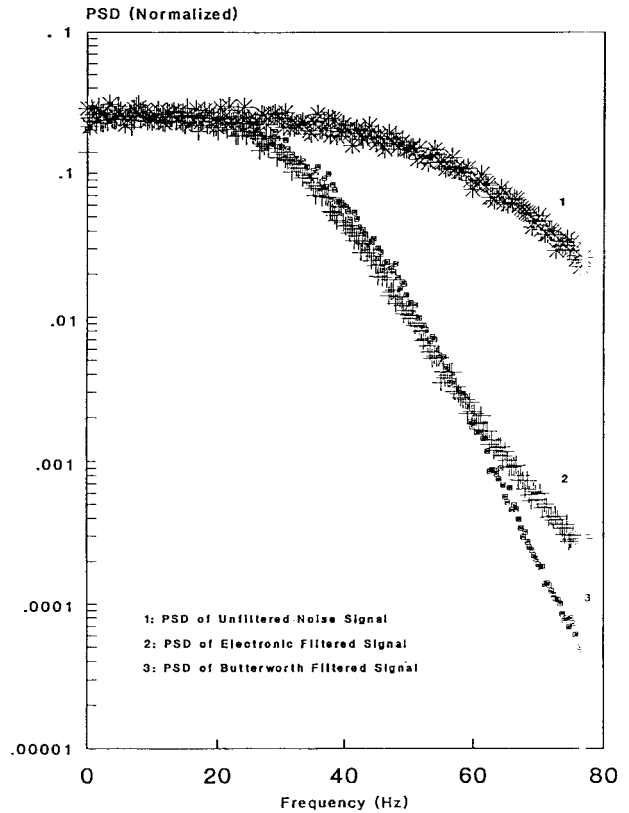
with a 50 Hz bandwidth was applied at the inputs of both filters, and the cutoff frequency of the filters was set at 20 Hz. The power spectral density (PSD) functions of the two filters signals are shown in Fig. 3 along with the PSD of the unfiltered white noise signal. As demonstrated in the figure, the performance of digital filter matches fairly well with that of the electronic filter.

3) Fast Fourier Transform: The main feature of the data processing algorithm is the fast Fourier transform (FFT) [16], which transforms the digital data in time domain into its frequency components. For this purpose, a recursive form of the discrete Fourier transform (DFT) is implemented, which accepts the sequence of digitized, time domain, vibration signal data and computes spectral coefficients. If h is the array of N consecutive sampled values of the signal $h(t)$, then the discrete Fourier transform of the Nth point, H_n is given by the relation [12]

$$H_n = \sum_{k=0}^{N-1} h_k e^{2\pi ikn/N}. \tag{4}$$

The resulting Fourier coefficients returned by the FFT routine are used for the computation of frequency spectral functions [16], power spectral density (PSD), cross power spectral density (CPSD), full and partial coherence functions and signal root mean square (rms) magnitude. Automatic peak search is also incorporated to identify the resonances in the frequency spectrum.
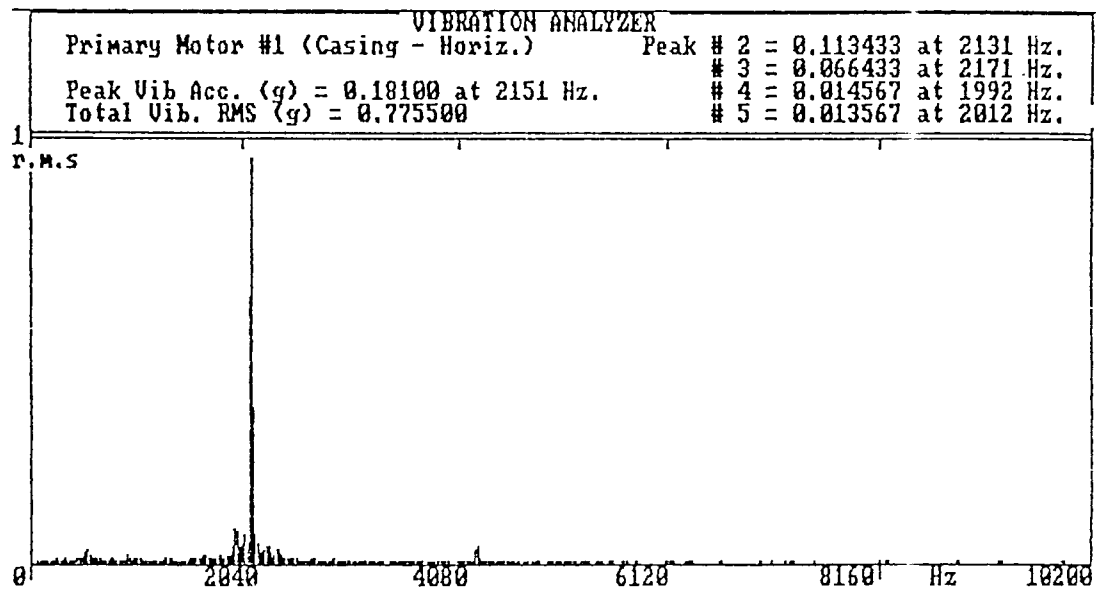
Fig. 4. Frequency spectrum of a sine wave signal obtained by the vibration analyzer.
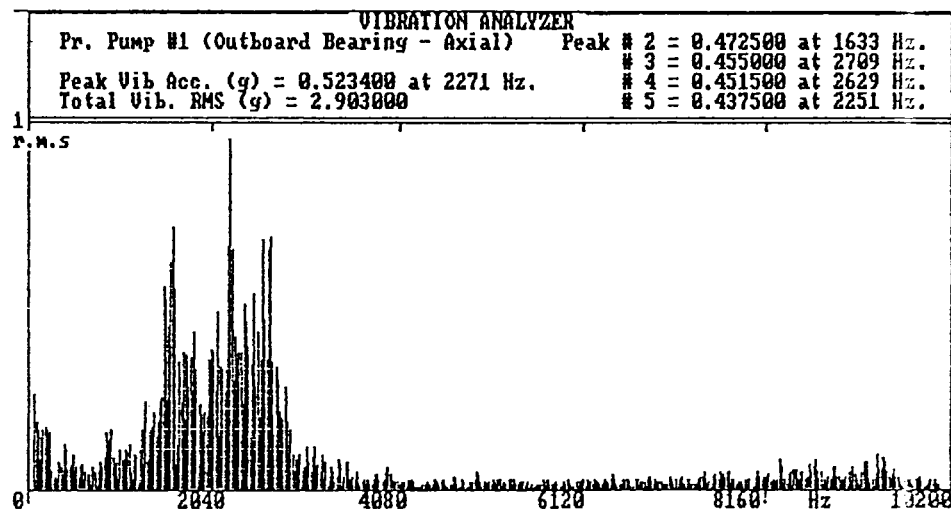

Fig. 5. Frequency spectrum of a wide band random noise signal.

4) Graphic Display and Data Archiving: For graphic display of vibration spectra and plots, subroutines were written in C-language. The graphic display card used was a Super VGA card with 1 MB RAM. All relevant information such as vibration rms magnitude, frequency and amplitude of the peaks, and the fundamental and harmonic numbers are also displayed on the screen. Provision of the printout of graphic display on the plotter and printer is provided. Archiving of vibration spectra of machinery obtained under different operating conditions and at different times is provided by storing the data on mass storage device of the PC.

5) Data Processing Execution Time: The execution time for data processing in VIBRATION program was compared on different computers. For a record length of 1024 data points the entire execution time was 0.4 s on a 24 MHz PC/AT-386 machine using SIMM memory modules. For a slower PC/AT

computer this time increased to about 1.3 s. This is a marked improvement over the execution time of other FFT algorithms on PC's reported in literature [17].

E. System Testing and Calibration

The performance of vibration analyzer was tested by applying calibrated sinusoidal and wide-band voltage signals, and analyzing their frequency spectra. Because of high signal resolution and good spectrum computation by the vibration analyzer, the spectrum of, for instance, a 200 Hz sine-wave signal having 5 V peak-to-peak magnitude, will be shown so that 90% of the total signal power lies in one peak at 200 Hz with only small side lobes. The frequency spectrum of a complex wide-band noise signal from a random noise generator is shown in Fig. 4. The rms signal power obtained
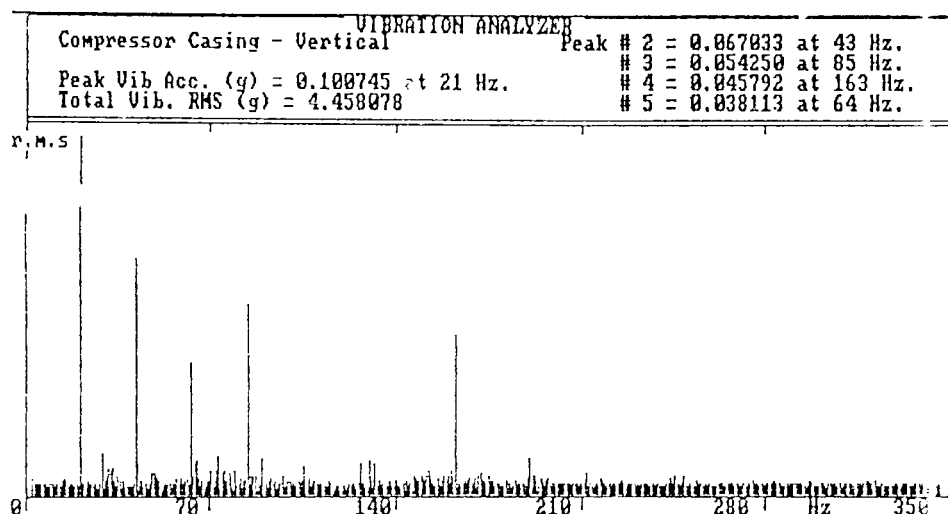
Fig. 6.   Vibration spectrum at primary pump no. 1 bearing box (axial plane).

by spectrum analysis also agreed with the rms settings of the noise generator.

The performance of the PC-vibration analyzer was also compared with the Hewlett-Packard spectrum analyzer (Model HP-3508/A) by applying vibration signals from a high-pressure air blower assembly. A close agreement was observed of the frequency spectra obtained from the two analyzers.

III. APPLICATIONS OF THE VIBRATION ANALYZER IN MACHINERY FAULT DETECTION

The following procedure has been adopted for the vibration monitoring of process machinery using the vibration analyzer.

- As the first step, the machine operating data, e.g., machine rpm, load, no. of impeller vanes, and the maintenance history are collected.
- The essential checkpoints of the machine are identified and listed.
- Vibration limits and expected tolerances are determined from the standard charts, and this data is stored in data files on the PC.
- The vibration transducers are then placed at the identified check-points and spot checks of vibration levels are obtained.
- Finally, multiplane vibration spectra of the machine are collected and analyzed for fault detection. These vibration spectra are properly labeled and stored for future trend monitoring.

The frequency spectrum of vibration of coolant pumps in the primary coolant loop of a research reactor are presented in Fig. 5. The vibration spectrum shown in the figure displays a complete pattern with a wide range of vibration frequencies, which are several orders of magnitude higher than pump's rotational speed. The total rms vibration acceleration at pump #1 was about 3 g. According to the vibration severity charts [4], the pump vibration amplitude

was excessively high. The probable cause of excessive vibration is the bearing defect, since the bearing noise gives rise to a wide range of vibration frequencies, each bearing component velocity producing individual characteristic frequency.

Another interesting application was the vibration analysis of the man air compressor in the reactor, which supplied air to the experimental facilities. The vertical-plane vibration spectra obtained at the compressor casing are shown in Fig. 6. The spectra exhibits harmonic behavior with peak vibration at 20 Hz and subsequent peaks at higher harmonics of 39 Hz, 79 Hz, and 160 Hz, respectively. One possible cause for this phenomenon is the vibration due to vortex shedding of the compressed air blowing through the compressor casing. The vortex shedding forces a surface to vibrate at frequencies which are the integral multiple of the fundamental frequency, and the magnitude of the vibration decreases with the increasing number. This phenomenon is being investigated.

IV. CONCLUSION

A PC-based vibration analyzer has been developed for fault detection and preventive maintenance of reactor components and rotating machinery. The use of a general-purpose PC and standard programming language makes the vibration analyzer simple, economical and adaptable to individual problems. The system can perform most of the functions available in complex, stand-alone vibration analyzers. It can acquire a maximum of 16 vibration signals with high, 12-bit resolution, and computes frequency spectra and rms amplitude of the vibration signals. The software is menu driven and user-friendly. With the help of C-language programming the vibration signals having large frequency bandwidth (up to 10 kHz) can be analyzed. The vibration analyzer has been used for fault detection in the heat transport system components of a nuclear reactor.

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