

Development of an Online Diagnostic System Software For Turbogenerator Set of Kakrapar Atomic Power Station

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ABSTRACT

An On-line expert system that works on a turbogenerator to monitor and detect faults, if any, has been developed. It is based on the vibration signature analysis concept using the vibration information as acquired from the turbogenerator's various bearing locations. These signals (20 shaft and bearing vibration signals distributed over six bearing locations supporting HP, LP and generator rotors) are processed and then analyzed using an expert system. The expert system uses Sohre's database and lists five most probable faults, if any, upon analysis. The software also displays trend of important vibration data continuously for better monitoring. The system is installed and operating on 220MW turbogenerator of Kakrapar Atomic Power Station.

Keywords: Online condition monitoring, Expert system, Turbogenerators, Nuclear Power Plant.

1. INTRODUCTION

With the advent of high speed, high power rotating machinery a sound maintenance program has become the need of the day. These machines develop some defects, which may be due to a design fault, or developed during the life of the rotor. Some defects progress slowly whereas some aggravate suddenly leading to a catastrophic failure resulting in total plant shutdown and thereby heavy financial losses (Rao, 1998a). Periodic measurements may be able to detect the slowly progressing faults, but not before substantial damage is already done. Periodic off-line inspections at frequent intervals are not foolproof while being too expensive. To reduce the costs if the intervals are set far apart it is highly probable that a defect may creep in and develop into a serious trouble before it is detected with the conventional maintenance program. Catching the defect early in its stage goes a long way in ensuring safe and trouble-free operation of these very costly and valuable machines. The bearings and blades failure of Narora Atomic Power Plant in 1993 (Rao, 1998a, 1998b) is the recent example indicating how continuous monitoring and online diagnostics could have avoided the unfortunate incident. An on-line diagnostic system thus becomes very economical and most efficient maintenance tool.

The vibration signature and its analysis have been in use for over two decades to correct the machine operation conditions to avoid failures. Hubbell (1978) records the operations in US Navy surface effect ship power plants' gearboxes using the vibration levels. Hill and Baines (1988) demonstrated the application of an expert system to diagnose faults for rotating machinery health monitoring. Here, the rule base was not well defined.

Most of the defects encountered in the rotating machinery give rise to a distinct vibration pattern (vibration signature) (Rao, 1996) and hence in most cases the faults can be identified using the vibration signature analysis techniques. The power plants use peak to peak or rms values to monitor the condition of the machine. But it has been found that any defect developed may not show any indication in the time domain data unless it deteriorates to an advanced condition. Whereas the frequency domain signal not only catches the problem early in its growth but actually tells, with certain probability, the

nature of impending fault like misalignment, or seal rub, or bearing failure etc. Sohre (1991) collected and compiled through his wide experience of over four decades of trouble shooting of rotating machinery in the form of several charts. This knowledge base is the most comprehensive that is available in open literature encompassing a wide variety of rotating and reciprocating machines.

The usage of Sohre's database in the application to an expert system for off-line condition monitoring of rotating machinery has been discussed by Rao et.al. (1994). Rao et al. (1996) applied this concept to monitoring of an aircraft engine. Rao and Shingote (1996) demonstrated how it could be applied in an on-line mode using simulated fault signals.

Commercially available current condition monitoring software for power plants do not have the capability to analyze the signals and diagnose the faults on-line using an expert system. They only trend rms values of vibration signals and display their frequency spectra. Significantly they lack several important features such as data backup, its storage, retrieval and display. Also they do not provide trending of amplitudes of important frequency components as well as on line expert system diagnostics. The software developed here is the first one to have all of the above mentioned features. The software not only diagnoses the machine condition with the help of Sohre's knowledge base but also manages to backup the acquired data and allows it to be retrieved for review.

2. OUTLINE OF THE SOFTWARE

The software uses two computers. Housed in the first computer (FDAS computer) is FDAS (Fast Data Acquisition System) which acquires the signals from the transducers mounted on the bearing and shaft locations of the turbogenerators. FDAS after acquiring the data feeds it to another computer (Main computer) which houses OLES. OLES, *On-line Expert System* deciphers the signals acquired in real time by first converting them from time domain to frequency domain signal and then using this frequency spectrum to infer about any possible fault. OLES also back up the data acquired to a separate backup

directory. It also updates the trend plot data that comprises rms value and the amplitude of various important frequency components of each vibration signal.

The main computer also houses OSBUDD (Operator Support and Backup Data Display) that supplements OLES. Since OLES constantly checks for and processes new data sent by FDAS, this separate and dedicated operator interface aids operator in interacting and viewing the acquired and processed data. This way OLES is left undisturbed in its task of checking and processing of fresh data in the background while OSBUDD caters to operator in displaying the acquired and processed data in the form of time domain, frequency domain, orbit plot, trend plot, etc. The expert system analysis results are also listed by OSBUDD upon request.

The screen of the main computer displays trend plot of any of the 20 vibration signals over a period of last week or last month or last year. By default trend plot of rms value of first bearing vibration signal will be available on the screen displaying last 24 hours of data. The displayed trend plot is automatically updated as and when the new data is acquired.

3. DETAILS OF FDAS

The data acquisition unit is a 8086 microprocessor based system with the recording being done on a high speed PC. FDAS acquires vibration data in three situations. First, it is programmed to acquire data at a predetermined time during a day, say 0100Hrs, 0900Hrs and 1700Hrs. Second, it acquires the data whenever rms value of any of the 20 vibration signals crosses threshold (lower or upper). Third, it can also acquire data upon operators' request. In either of these cases the acquired data is transferred to main PC.

The acquired data comprise 20 vibration signals. Two process signals acquired are Generator Power and Condenser Vacuum. 12 vibration signals are acquired from bearing sensors (velocity transducers) and 8 vibration signals from shaft sensors (non-contacting eddy current probes). The bearing signals are tapped from Turbovisory panel and the shaft signals from the on-line shaft monitoring system. The vibration channels are set

with a predetermined threshold level. FDAS is connected to the FDAS PC by a high speed LAN for transferring data.

Each vibration signal is represented by 5000 samples at sampling frequency of 5KHz. Each process signal is represented by 4000 samples at sampling frequency of 100Hz. Thus the vibration signal acquired for a total of a second gives sufficient data for converting vibration signals from time to frequency domain. Each signal also carries information regarding whether the signal is taken due to threshold crossing (upper or lower) and if so, which signal crossed the threshold. This information is maintained by OLES when it updates trend plot data.

4. WORKING AND DETAILS OF OLES

Working of OLES is divided into following distinct tasks:

- Check for fresh data and back it up
- Analysis of acquired data and updating trend plot data
- Diagnosis of a fault using Expert System.

Fig.1 shows details of working of OLES.

Check For Fresh Data And Back It Up

OLES keeps track of fresh data sent by FDAS. The OLES has an in-built function that keeps checking for new arrival of input time domain files from DAS. This function when it detects arrival of new set of data kicks off data processing cycle that starts with first converting the input time domain text data to binary format. These 20 time domain signals in binary format are stored to a backup directory in a single file whose name is representative of the date and time at which the data was received. The file name is constructed as follows.

The file Tddttttt.bar is stored in Mmm subdirectory of Yyyyy directory in the backup directory named BACKUP. Here, dd: the date, ttttt: the time, M: month tag, Y: year tag, mm: the month, yyyy: the year. For example, a signal acquired on 23rd of May 1998 at 01:45:28 will be named N23014528.bar and stored in M05 subdirectory of Y1998 directory in the BACKUP directory.

In the main PC only one directory named OLESDATA is allocated for the recently acquired time domain data. This data is overwritten by the next acquired data, whereas in the BACKUP directory all the acquired data is stored to a well-defined directory structure.

Analysis Of Acquired Data And Updating Trend Plot Data

The Fast Fourier Transform is performed on each of the 20 time domain signals. The rms value computed from the time domain signal and amplitude of vibration at predominant frequencies of interest obtained from frequency domain signal of the 20 signals are stored in a special trend record format as shown in Fig.2. This information is useful for the purpose of trend monitoring. The already existing trend plot data stored in trend plot files stored in BACKUP directory is updated by OLES. Two other parameters viz. Generator Power Output and Condenser Vacuum are also stored along with the above data. The trend data is segregated in four separate files, namely, the previous day file, the last week file, the last month file and the last year file.

Diagnosis Of A Fault Using Expert System

After performing FFT on the time domain signal and updating the trend plot, OLES calls the expert system module which first identifies the presence of important frequency components in the frequency spectrum of all the shaft and bearing vibration signals. This information is then input to the expert system module which after taking into account the type of signal (bearing or shaft), direction of signal (horizontal, vertical or axial), computes probability of existence of each fault in the signal being analyzed. The expert system uses the probability table compiled by Sohre (1991). It is well known that a particular fault generates a typical frequency pattern. If the frequency components identified match with that of the frequencies generated by any of the known faults then the current signal may be generated due to the fault whose frequency pattern is found to be matching. In this way the presence if any of a fault in the signal can be detected. But a particular frequency can be generated by more than one fault. By attaching probability values to each fault depending on presence of frequencies as given by the Sohre's database, the overall probability of each fault in the given signal can be computed.

5. WORKING AND DETAILS OF OSBUDD SOFTWARE

The OSBUDD basically works on the backed up data processed by OLES. The purpose of the OSBUDD is to allow the user to view in various formats the data already acquired and processed by OLES. Refer to Fig.3, showing details of working of OSBUDD.

OSBUDD has following modules as shown in Fig.4.

- Plot – Time Domain
- Plot - Frequency Domain
- Plot - Trend
- Plot - Orbit
- Plot - Waterfall
- Analysis - Expert System
- Analysis - Signal Processing
- Load Backup Data
- Configure
- Assistance - Demo
- Assistance - Help

Time Domain Signal menu displays the time domain signal in the backdrop of bands of different colors indicative of severity of vibrations. For example a cyan color band that starts at vibration velocity of 3.5mm/sec indicates “allowable” vibration category. Beyond that a yellow color band which starts at 9.2mm/sec indicates “not allowable” vibration category and so on. These ranges are arranged according to ISO standards for 3000rpm machines. The numbers on the x-axis are the sample numbers of the time domain data and the amplitude value of the samples are displayed on the y-axis. Cursor position can be changed by using arrow keys or buttons provided at the left side of the signal or simply double clicking the left button of the mouse at the position of interest. The sample number and corresponding amplitude value of the current position of the cursor is also displayed there. Any other signal of interest can be chosen for display, using *Signal Selection* module available at the top left corner of the screen. The same can be achieved using two triangular buttons provided there. The axis limits of the time

Comment [PJSR1]:

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domain display can be set using *Change Limits* button. To get a magnified view of a part of the signal operator can click right button of the mouse. *Refresh* button brings back the original display. A sample time domain signal display is shown in Fig.5.

Frequency Domain Signal menu shows the Fast Fourier Transform of the time domain signal. Radix2 algorithm is implemented on 4096 samples of the data collected. The inherent noise in the signal is minimized by auto correlating the signal before transforming it. The frequency domain signal is shown enclosed within the background of different bands corresponding to healthy values. These healthy values are decided using past recorded data. There are two bands, one corresponding to allowable limits and the other for not satisfactory limits. The x-axis values are frequencies and the y-axis values are the corresponding amplitudes. Other things are similar to Time Domain Signal. A sample frequency domain signal display is shown in Fig.6.

Trend Plot loads trend plot data previously stored by OLES in trend plot files and displays default trend plot. Operator can modify the display to show trend plot for any specified period. The trend may be of rms value of a particular signal or it may be of any frequency of interest like 50Hz. The trend plot of bearing vibration signal in all the three directions is shown together so as to correlate variation in these signals. A toggle button is provided to swap the display to show both shaft (vertical and horizontal) signals together. The trend plot is always shown in conjunction with Generator Power and Condenser Vacuum so that if disturbing trend in rms or frequency value is due to transient changes in above two process parameters, possibility of any fault can be tentatively ruled out. Mostly when these two parameters are within limits and if the trend of the signal is disturbing, it is then the possibility of any fault creeping in should be looked into. This way these trend plots help in better and comprehensive interpretation of the condition of the machine. Screen snapshot of trend plot is shown in Fig.7.

Orbit Plot displays locus of the rotor center drawn using a pair of vertical and horizontal shaft vibration signals. The menu allows to chose any location for which the orbit plot is to be drawn. The plot can be of use to diagnose some faults from the shape of the orbit.

Waterfall Plot menu displays waterfall plot for the coast up data that can be acquired during startup process of the turbogenerator. The frequencies are shown on x

axis, the rpm reading on z axis and the amplitude on y axis (vertical). The peak at the first critical speed is clearly seen. Speed range over which the waterfall is to be viewed can be set as also the angle of view and frequency range of interest. A simulated waterfall plot is shown in Fig.8.

Expert System menu displays list of five most probable faults that the current signal may indicate to. Since the expert system analyses the signal accounting for the relative dominance of amplitude of various frequency components in all the three directions and also for the type of signal (shaft or bearing), all the bearing and shaft signals available at a location are used in the analysis. Hence the expert system analysis results are available location wise. Operator may view the analysis results at different locations by choosing any location from the location selection box provided (Fig.9).

Signal Processing menu is in itself a dedicated signal analysis toolbox that allows operator to test the quality of each signal (Fig.10). It has following menu options.

- Coherence
- Correlation
- Correlation factor
- Cross spectrum
- Convolution
- Signal/Noise Ratio
- Phase plots

This toolbox helps operator to assess extent of linear dependence of one signal over the other, similarity between two signals, to discern the frequency range in which the noise or disturbance is most significant.

Load Backup Data loads backed up data stored in the BACKUP directory by OLES. This data basically is time domain signal at all locations acquired at a particular time. The user then can review this data like any normal data. This facility is provided to allow operator to check any previous data. Sometimes from the trend plot a particular instance of data may necessitate a closer look and review. Noting the time and date of the interested data sample from the trend plot the operator may use *Load Backup Data* menu to load this instance of data that may be analyzed from a different perspective. Expert system analysis for this data can also be viewed.

The menu first allows operator to modify the default path of the BACKUP directory (Fig.11). Normally the path as earlier mentioned is C:\BACKUP. However if the backed up data is to be loaded from other storage device such as a CD, then the operator may modify the source directory path in the edit box provided at the top. This is helpful when large data accumulates in the BACKUP directory of the computer and needs to be transferred to another auxiliary storage device to make space in the local disk. Having specified the source directory path, operator can choose the day, month and year of the data of interest from the *date selector* provided in the dialog box. Once this is set, a list of instances of data acquired on the selected date is made available in the *Available Files* list box. Choosing the appropriate time instance of data from this list box the operator can load the data by clicking on the *Load File* button. The dialog box has another option of loading latest data acquired by OLES.

Demo module assists the operator to know more about various faults commonly encountered in turbogenerators. About 23 faults are described in detail along with the simulated time domain and frequency domain plot for the fault signal (Fig.12). Simulated signal is generated using established frequency pattern of a given fault. A list of predominant frequencies and their corresponding relative amplitudes is also displayed. This may help the operator to understand the typical time domain plot and predominant frequency contents of the vibration signal generated by a specific fault. Acquaintance to vibration signature of various common defects using this module is expected to arm him with basic knowledge to better deal with what he observes in practice.

Help module gives a detailed information about everything the software has to offer. It also describes the overall working of the complete software. Each module is explained in detail. One of the most interesting features is the *Interactive Mode* that allows the operator to click on any part of the dialog box of any module and get information about it. For this purpose dialog box of each module are displayed in the help files.

Configure menu option is used to customize the display settings like what should be the default x-axis and y-axis limits of the time and frequency domain signals as well as trend plots. It also helps in setting the healthy limits of some of the predominant frequencies. Settings for the severity bands in case of time domain plot can be done. The

main configure menu box is shown in Fig.13. Using this various menu options can be configured. For example, the configuration of trend plot can be done through Trend Plot Configuration Box as shown in Fig.14.

6. CONCLUSIONS

Comprehensive on-line condition monitoring and diagnostic system software for turbogenerators of Kakrapar Atomic Power Station (KAPS) is developed. The software developed is housed in two computers. The on-line analysis of the vibration signals, trending of key vibration parameters and early detection of a possible impending fault is the key feature of this software. FDAS acquires the data from the transducers mounted on various bearing and shaft locations of the turbogenerator, OLES analyses it and OSBUDD provides most user friendly interface. The data is continuously trended and displayed in various formats such as time or frequency domain, orbit plots etc. A systematic backup of the acquired data is maintained in the backup directory. This enables viewing and analyzing of the data at a later date.

Another key feature of the software is the use of an expert system utilizing the knowledge base compiled by experts in this field. This expert system gives prompt advise regarding the possibility of the most probable faults so that the operators can plan an appropriate maintenance schedule well in advance and minimize the down time.

The software has been installed at KAPS and running successfully since then. The plant maintenance personnel are using it to monitor the condition of the turbogenerator.

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WORKING OF OLES

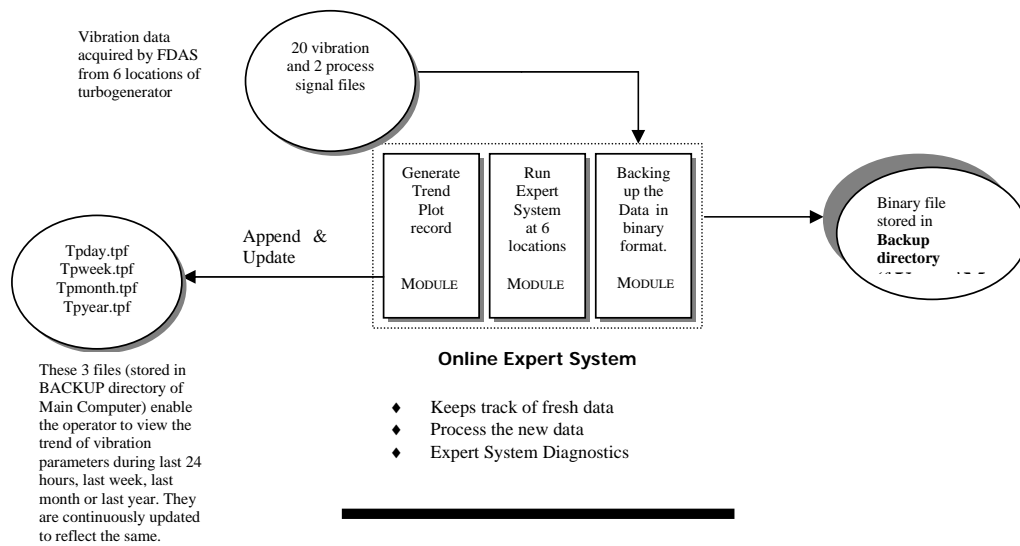


Fig .1 Working of the OLES

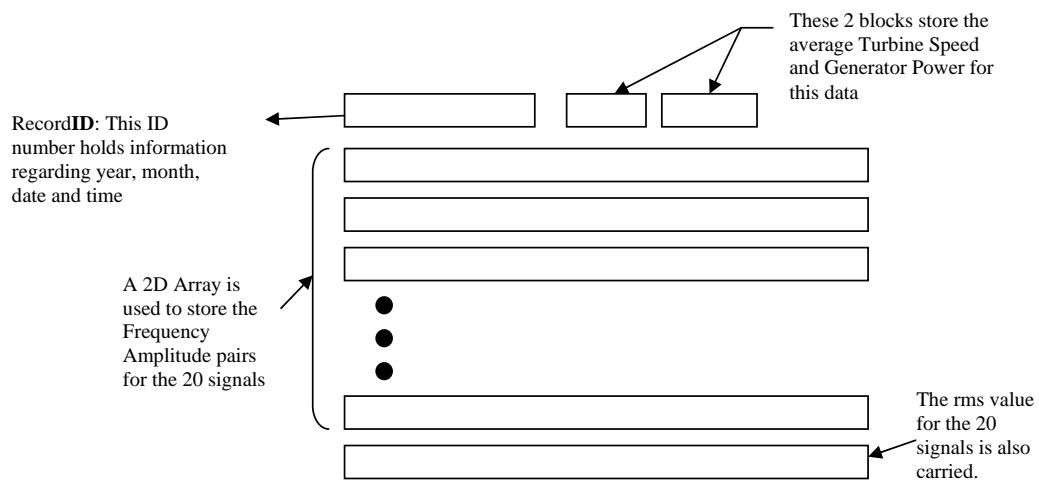


Fig.2 Structure of a Trend Plot Record

WORKING OF OSBUDD

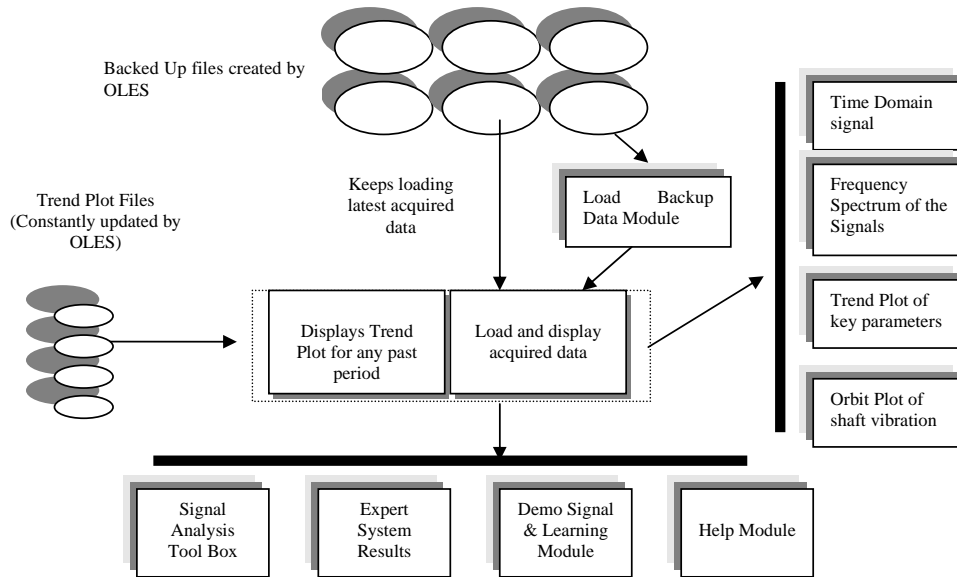


Fig.3 Working of OSBUDD



Fig.4 The OSBUDD Menu Screen

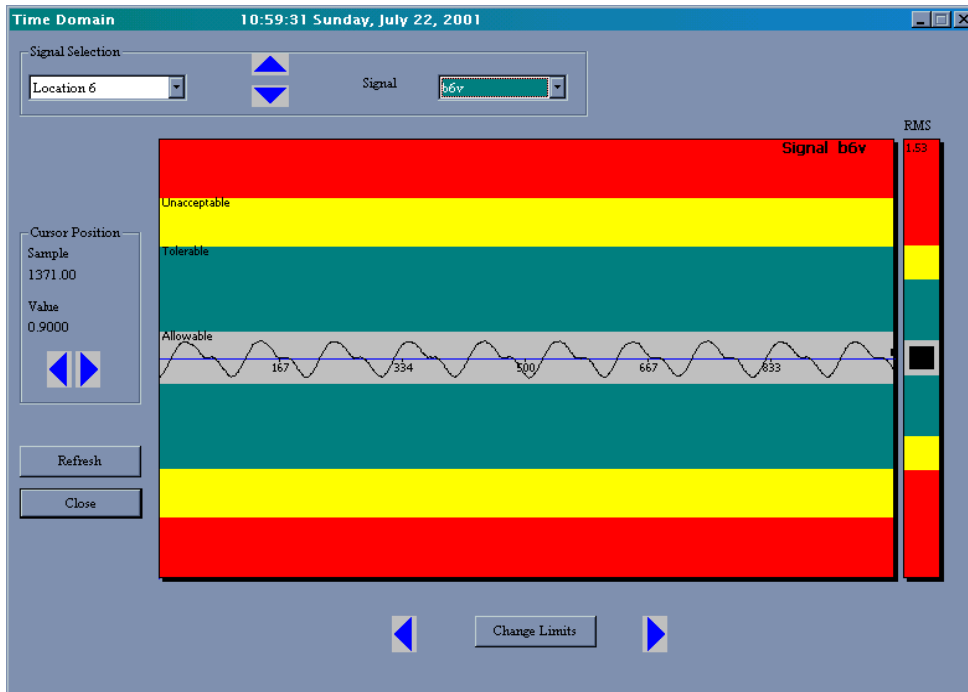


Fig.5 Screen Snapshot of Time Domain Signal

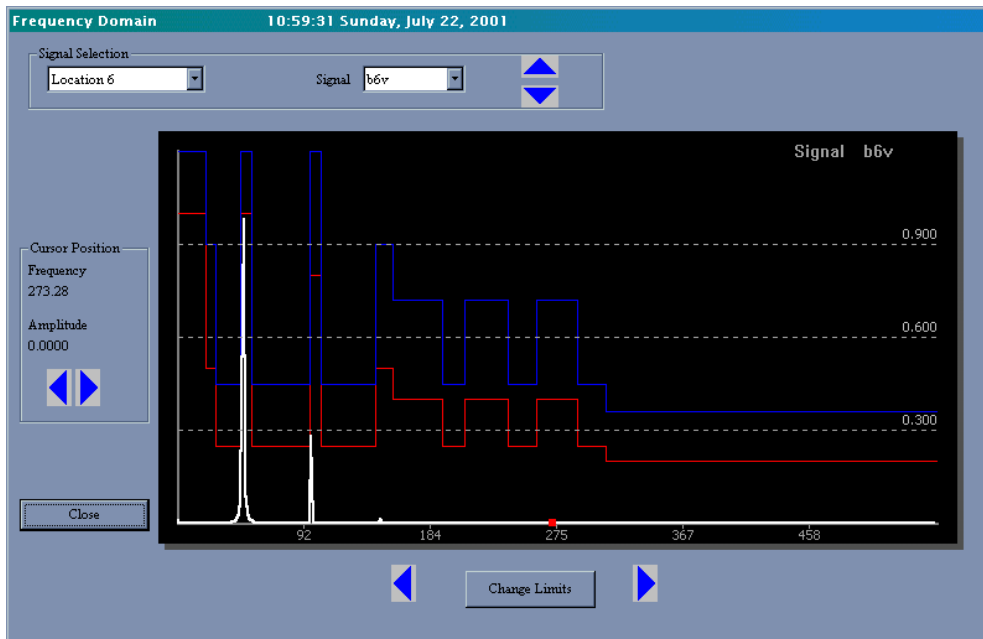


Fig.6 Screen Snapshot of Frequency Domain Signal

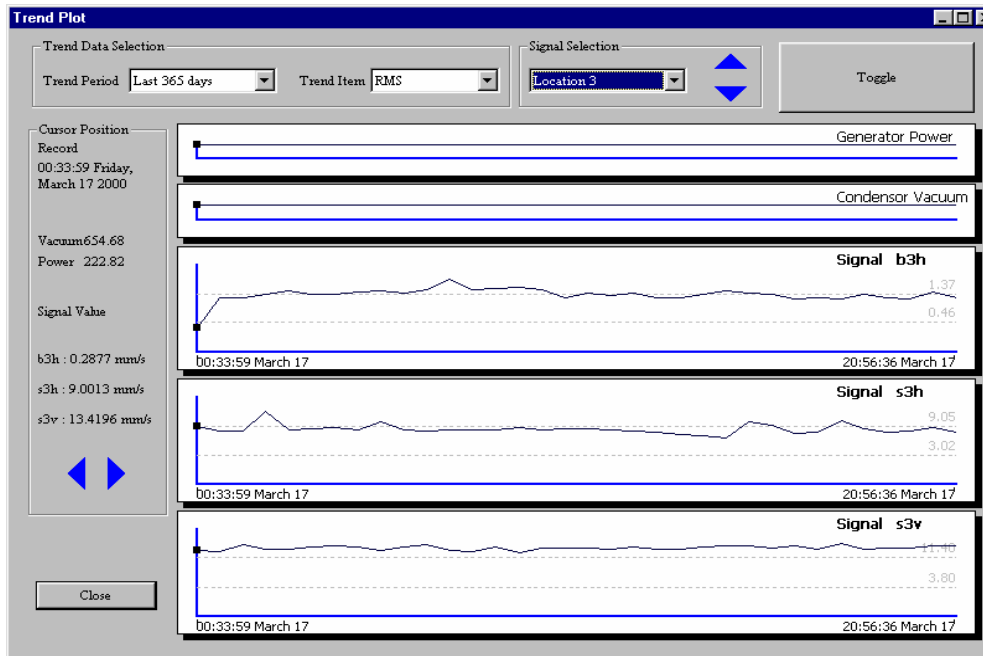


Fig.7 Screen Snapshot of Trend Plot

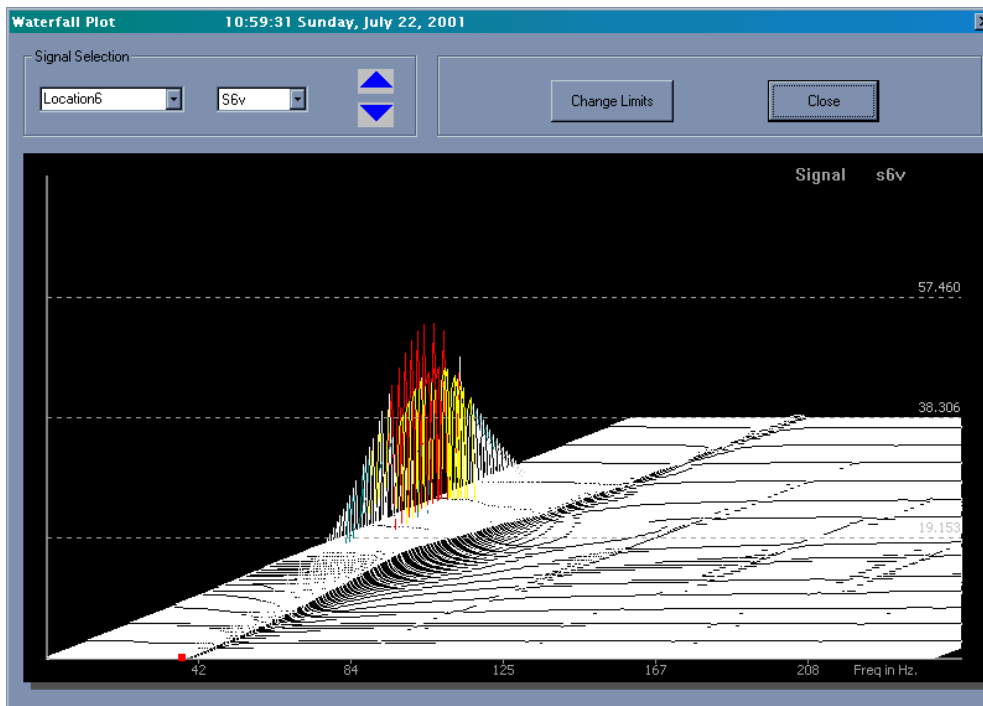


Fig.8 Screen Snapshot of Waterfall Plot

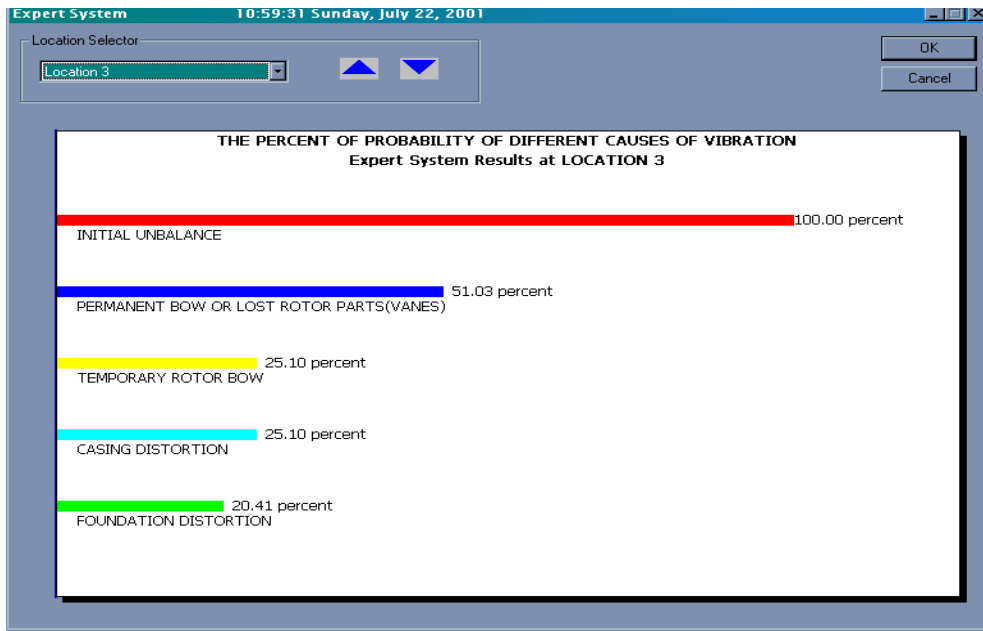


Fig.9 Screen Snapshot of Expert System Results

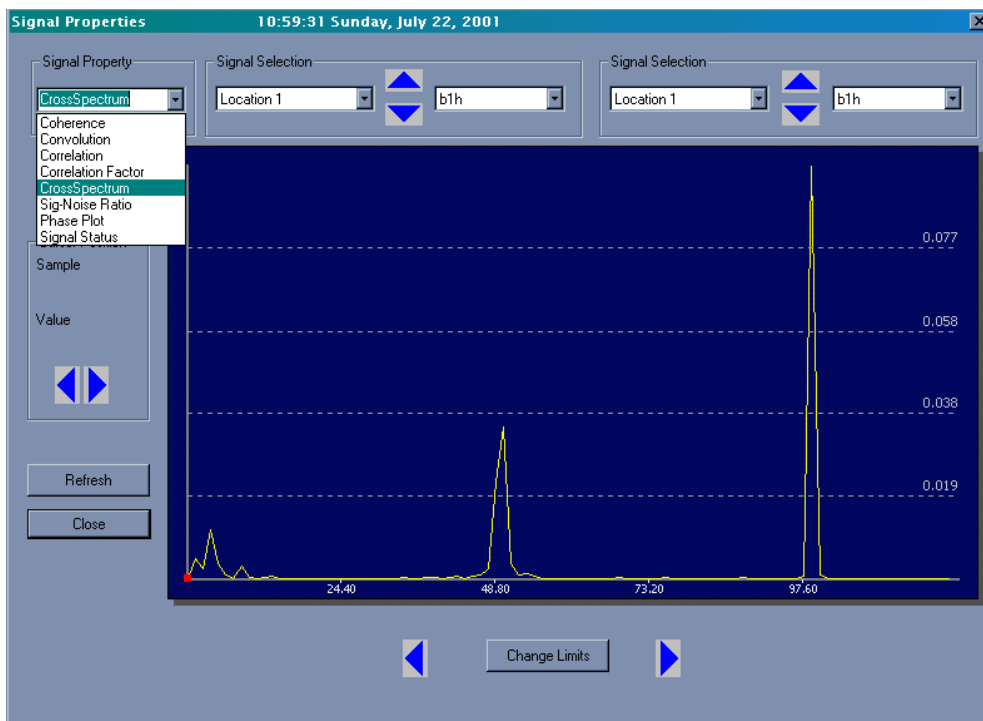


Fig.10 Screen Snapshot of Signal Properties Tool Box

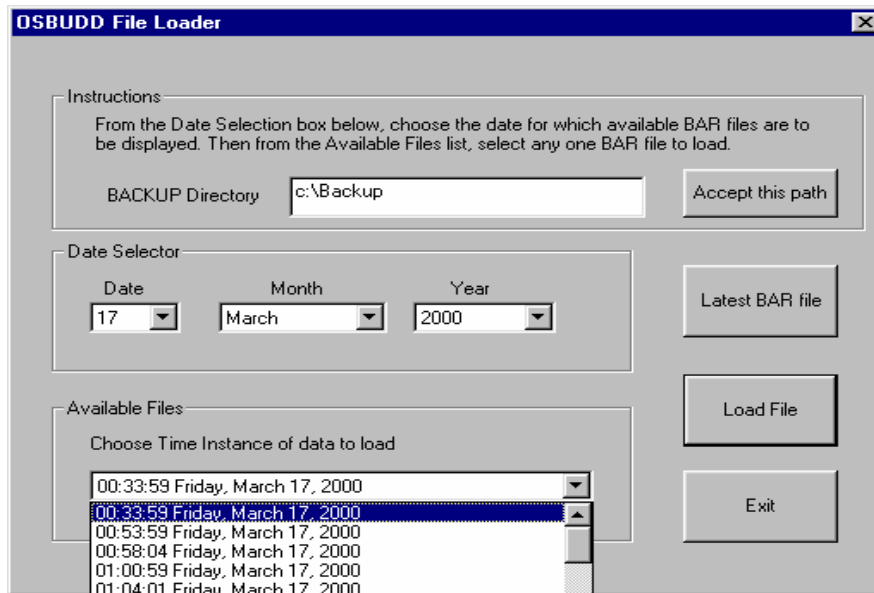


Fig.11 Screen Snapshot of Backup Data Loader

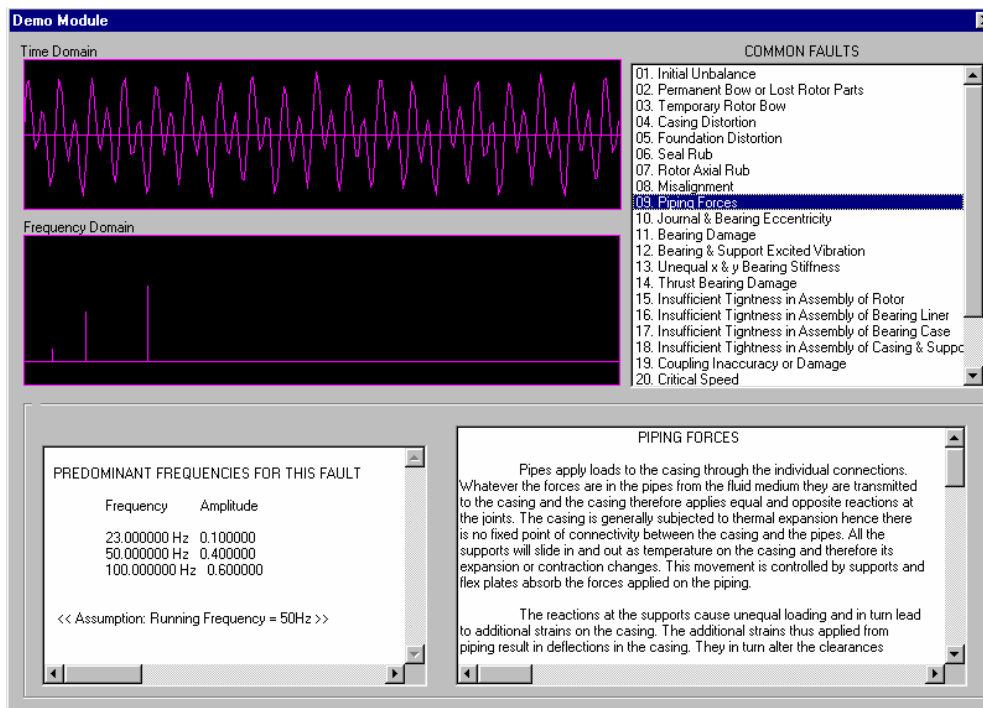


Fig.12 Screen snapshot of Demo Module

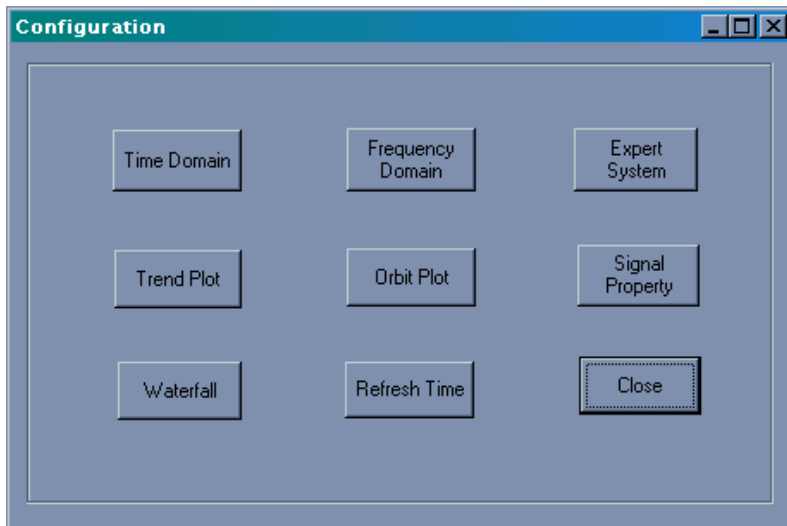


Fig.13 Screen Snapshot of Configuration Menu Dialog Box

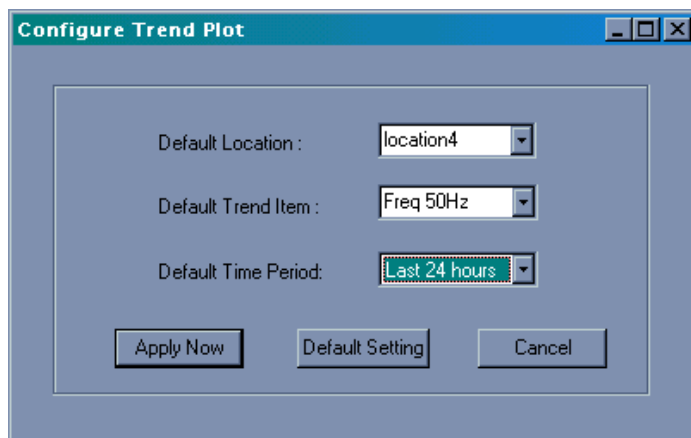


Fig.14 Screen Snapshot of Trend Plot Configuration Dialog Box