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Research Article

Growth in Vibration Measurement Techniques for High Speed Machines – Case Study of Power Plants

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Abstract

During the last 50 years, there has been a good level of quality research in the field of material science, structural design, manufacturing techniques, installation methods and quality control of power plant machineries. All this has led to reduced factor of safety, higher slenderness ratio, but better operational performance. Also, the operating speeds have gone up and machines with better efficiency and higher levels of outputs are now possible. With such developments, however, the machineries become more prone to vibrations resulting into complexities to control and keep them within safe limits. Under such circumstances it is essential to identify any abnormal condition as soon as it arises and prevent the machineries from damage and consequent failure. The growth and development of the vibration measuring techniques has been phenomenal. Today, we can do accurate analysis to exactly locate the problem, but this was not possible, a few years back. This paper attempts to define the path of journey with major milestones, from a simple vibration measurement in mV units some 50 years ago to present day recording of complex vibration spectra for exactly pointing out the cause of vibration with a higher degree of reliability.

Keywords*: Vibration, Frequency Analysis, Magnetic Tape Recorder, FFT, Condition Based Monitoring, Signature, Spectrum.*

1. Introduction

As far as the power plants are concerned, the downtime is very costly. For economic operation of machines, deeper study into the vibration behavior of rotating machineries has to be carried-out in today's perspective. Vibration is an important indication for the operating condition or health of any rotating machine. The data obtained by observing vibration amplitudes in appropriate units at specific locations and corresponding frequencies can help a vibration engineer to a great extent in pin–pointing the cause of abnormal vibrations. This results into short and planned periods of shut-downs and ultimately leads to prolonged uninterrupted running of the machine. The performance and productivity of power plants can ultimately be improved.

About half a century back neither proper sensors, nor proper measuring instruments were available. The earlier instruments used to measure vibrations in electrical units which had to be converted into mechanical units as direct measurements in mechanical units were not possible. In the absence of such advanced instrumentation, however, the flaw defection and failure prediction were not so easy in the past. At present, however, quite sophisticated vibration instruments are available, which are capable of providing good data for understanding the vibration behavior of machineries. In the present scenario, it is quite convenient to hold a portable instrument in hand and connecting it to a light weight sensor placed on a rotating machine, record the vibration spectrum and split it into its frequency contents. Multichannel instruments are available for taking real time data which can be stored and analyzed by experts at a later time. Similarly for the determination of natural frequencies and mode shapes of components and structures, one has to only bang the system using a piezoelectric hammer and record the resulting signal showing all the natural frequencies. Also, it can very easily be viewed as how a shaft is actually moving within its bearings by observing the orbital plots. As far as continuous monitoring is concerned, advance Data Collectors are available for portable as well as Control Room application. All this development is a result of slow but steady growth in the fields of electronics signal processing, instrumentation engineering and computer technologies. With such advancements, it is now possible to identify the possibility of a flaw or that of a failure at an early stage and abrupt failures can now be avoided.

2. Mechanical Devices

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Anybody can have a feeling of unwanted vibrations by just standing near a rotating machine. If the machine is having some problem viz. unbalance, misalignment, looseness, resonance etc; then the vibration level may be too alarming and an immediate need to control this vibration can be felt. People standing near the machine may feel fear of an accident or may get irritated due to unpleasant noise caused by vibrations. Thus it can be understood that with the start of application of rotating machines in industry, the engineers must have realized that a study of origin of vibrations and methods to control them is essential.

As far as measurement of vibration is concerned, in early days of 1940s & 1950s, a coin was placed on vibrating components and if it did not fall, it was considered to be a good machine. Vibrations were also felt by screw – driver or by index finger. Later, mechanical devices came into existence. General electric developed a Reed Vibrometer which used a resonant vibrating reed with superimposed scale to measure vibrations in mils (a mil is equal to a thousandth of an inch). GE Reed Vibrometer used a pantograph mechanism and a clock movement. Similarly for measurement of frequency, Vibration Reed Tachometers were used. It consisted of an extended series of reeds of various lengths mounted on the same base. The device was placed on a vibrating surface and the frequency was determined by observing which of the reeds is vibrating at its natural frequency.

3. Overall Amplitude from mV Readings

The initial disclosure of vibration measurement for industrial applications was made in a paper titled, "Vibration Tolerance" which was published in 1939 issue of the journal, " Power Plant Engineering". The author of the paper was T.C. Rathbone who was working as Chief Engineer in an established Turbine & Machinery manufacturing company of New York. Rathbone developed "The Rathbone Chart" which compared overall vibration velocity to varying degrees of machine smoothness. He, however, made no reference to frequency content of the vibration, or to the size and capacity of the machines. Rathbone, later presented a guide for assessment of machineries operating condition on vibration displacement in the frequency range of 60 to 7200CPM. The concept given by him in 1939 about relating the machine condition with respect to vibration amplitude is significant even today and the latest concept of condition monitoring is based on this.

During the initial time of measurements by electronic devices, vibration was measured in electronic units viz. mV. Bruel & Kjaer Denmark make Measuring Signal Amplifier, B & K 2606 (fig. 1) was used for measuring signal in mV using a pickup with known sensitivity in mV / g. From conversion slide rules the signal was converted into g (acceleration), from which velocity or displacement unit was determined. Only overall vibration measurement was possible and its resolution into frequency components was not possible.

In early 1950s, another vibration instruments manufacturer, IRD Mechanalysis of USA developed a velocity pickup, model IRD 544 (Fig. 2). This was an electro–mechanical, moving coil type pickup with sensitivity in mV per in / sec. A voltmeter was used to record the mV signal which could be converted into velocity parameter using the sensitivity of the pickup.

Fig.1: Measuring Amplifier B & K Type 2606

Fig.2:IRD Model 544Velocity pick-up

4. Overall Amplitude in direct vibration units

The process of converting mV units into vibration units was quite cumbersome. In case of abnormal vibrations, the machine could not be stopped as mV was not representing the severity. This could lead to failure of components. A need was therefore felt to have vibration readings in direct displacement units. IRD Mechanalysis developed an instrument IRD – 308 (fig. 3)

Fig.3: IRD Sound & Vibration Meter, Model 308

Fig.4: B & K Vibration Meter Type 2511

for measurements of vibration in direct vibration units. They used their velocity pickup IRD–544 with IRD 308 for display of vibrations in displacement and velocity units. The velocity signal could be integrated to read displacement. Similarly, Bruel & Kjaer, Denmark developed a Vibration Meter Type 2511 (fig. 4) and used a piezoelectric charge accelerometer type 4370 (fig. 5), as a sensor. The acceleration could be integrated twice first to velocity and then to displacement. The Meter could read overall vibration in displacement, velocity and acceleration mode. The readings could now be taken for overall vibrations but the break-up to frequency components was required to find out which part is causing the problem. The need for vibration analyzers was therefore felt.

5. Need of Overall Amplitude with Frequency

The overall vibration amplitude measured by vibration meters is basically a fourier summation of all the frequency components present in the system. Although, overall vibration level could indicate the severity of vibrations to some extent, it could not help in exactly detecting the fault. It was felt that if we can somehow identify the contribution of each frequency present in the system we can get a better idea about the actual cause of vibrations.

Fig. 5: B & K Accelerometer Type 4370

Fig.6: B & K Tunable Band Pass Filter Type 1621

By splitting the overall amplitude into its respective frequency components, it can be found as which are the prominent frequencies in the system. By identifying the source of these frequencies, one can find out the defects which are causing high vibrations. To meet this demand of power plant industry, Bruel & Kjaer, Denmark developed a Tunable Band Pass Filter, B & K Type1621, which could be connected with vibration Meter Type 2511. By tuning the frequencies manually on 1621, the peaks of amplitudes were observed on 2511. Frequencies corresponding to peaks were recorded manually and this type of manual frequency analysis of vibration was used to diagnose the problem. But, two separate instruments were to be used which was again not a desirable feature. To overcome this difficulty, IRD Mecanalysis, USA developed a better instrument & called it, Tuned Filter Vibration Meter, model 1970. In this case, the filter was built–in and vibration analysis was possible using a single instrument. For recording of spectrum, separate recorders were then added. IRD developed its model 1080 Vibration Baseline Recorder. Bruel & Kjaer added strip chart recorders. IRD also developed other Analyzers model IRD – 345

Fig.7: IRD Vibration Analyzer Model 345

Fig.8:IRD Portable Vibration Analyzer/Balancer

and IRD – 360. These equipments had built in tunable filter but separate pen recorders were to be connected for recording signal. They later developed an advanced version model IRD – 880, which had a built- in recorder to generate a frequency spectrum at one particular location at a time. These equipments were known as Vibration Analyzers as they could detect the vibration amplitude along with frequency. By 1960s and 1970s several Companies were manufacturing Vibration Analyzers with built – in recorders. These Companies were:- Spectrum Dynamics, Bentley Nevada Corporation (it later become GE energy optimization and Control), Wavetek (later known as Rockland Scientific Corp.), General Radio, Schenck, IRD Mechanalysis (later Entek and now Rockwell Automation) and Bruel & Kjaer, Denmark, etc.

6. Magnetic Tape Recorders

The data recorded on vibration meters / monitors is normally overall amplitude. However, for diagnosing the problem, it is necessary to break the overall amplitude to its frequency components. Vibration analyzers are used for this purpose but manual recording has to be done one by one on different locations of the machine. It takes a long time to cover all the locations and in case of a machine having abnormal vibrations the machine cannot be run for longer duration and complete data cannot be obtained. Magnetic Tape Recorders (MTR) could overcome this problem by putting probes at several location and connecting them with a multi – channel MTR for simultaneous recording.

Stefan Kudelski, a Polish Audio Engineer in 1957, introduced the first ever audio recorder named, “Nagra III”, which was a transistorized tape recorder with electronic speed control. The more developed versions of this audio tape recorder were introduced in 1960s and 1970s. However, it was in 1980s that some of the Companies started the Commercial application of Magnetic Tape Recorders for recording the vibration signal for condition monitoring. Bruel & Kjaer introduced type 7006,

Fig.9: B & K Magnetic Tape Recorder Type 7006

4 - channel instrumentation tape recorder. At the same time Companies like Lockheed Electronics, Honeywell, Spectrum Dynamics and Hewlett Packard brought their match in the market. The earlier Tape Recorders were quite heavy in weight and they used separate pre–amplifiers and vibration transducers. Bruel & Kjaer Tape Recorder used separate pre–amplifiers for each channel. Due to heavy weight and separate pre–amplifiers etc the portability was not good and their application was restricted to Plants only. Special packings for safeguarding them during transit were required in case of transporting. These Tape Recorders were available with both direct (AM) and frequency modulated (FM) channels. The FM recording was preferred to have a linear response even at very low frequencies (DC included).

The signal recorded by MTR could later be played on an Oscilloscope, to study the prominent frequencies for fault diagnosis purpose. Several manufacturers followed B & K and brought their models of Tape Recorders in the market. The oscilloscopes have today been replaced by FFT Analyzers.

7. Vibration Monitors

At this time, operation engineers in Power Plants started feeling a need of having measurements on continuous basis. When a machine runs for 24 hours a day for months together, a problem may generate at any odd hour of the day. If that data regarding increase in vibration level is not observed at right time, it may lead to damage in some part of the machine. Failure to obtain the data can also make it difficult to find out the cause of the problem.

To meet this requirement of the industry, vibration monitors were developed. Bentley Nevada was one of the initial companies to produce monitors. The monitors were installed in the Control Room and were connected through cables to transducers mounted on the various locations of the machine. When the vibration level at a particular location exceeds the permissible level, the machine can be automatically tripped after getting appropriate signal from monitors. Continuous recording on recorder paper was also made possible. But, only overall vibration was recorded and therefore, much useful information was not obtained. It was felt that there has to be some way to record the complete spectrum for better fault diagnosis.

8. FFT Analyzers

Prior to introduction of FFT Analyzers, two types of problems were faced by vibration engineers. Firstly Vibration data was recorded in time- domain, mostly on two- channel oscilloscope. A periodic waveform indicated the presence of a single frequency. However, the actual machines used to have presence of several frequencies simultaneously and their identification was not possible. The overall vibration is the fourier summation of all the frequency components present in a system. As per Fourier theorem, any waveform in the time domain can be represented by the weighted sum of pure sine waves of all the frequencies.

The spectrum analyzers were therefore developed to represent the time domain signal by its component frequencies. Initially, Analog Spectrum Analyzers were used, in which an analog filter was used to select the desired frequency. This required manual tuning of the filter to read the amplitude at those frequencies. Later on, the spectrum analyzers with auto-tuning filters were developed so that spectrum records could be taken by using external or built – in recorders. IRDs model 360, 345 and 350 with external recorders are examples of initial analyzers introduced in 1970s. In 1980s they introduced IRD-880 which had a built – in recorder having wax-coated paper roll. Resolving the problem of measuring frequency components resulted into Signature / Spectrum Analysis. When the machine was first commissioned, a frequency spectrum was recorded and this was known as Signature. At appropriate time intervals, these spectrums were again taken and observation was made regarding any variation from the basic signature. From this comparison, it could be found as what type of problem is being generated and proper solution could be planned to overcome the problem.

Another problem for vibration engineers was with regard to real time data. Large machines like steam turbine & turbo-generator used to have 8 to 10 bearings. With spectrum analyzer, the signal could be recorded one by one at location and it could take few hours to record the spectras. At a time when vibration level was quite high & beyond the permissible level, it was not practical to run the machine for a longer duration as it could cause damage / failure. Also, when measurements are taken at a particular location, the vibration spectrum could vary at locations where the records were taken prior to current location. As such, the possibility of loss of real time data was there.

Introduction of FFT Analysis techniques provided a solution to these problems. With the use of multi–channel FFT Analyzers, the frequency plots could be taken in real time domain. The development phase of FFT Analyzers has witnessed a lot of challenges viz. technical barriers, selection of measuring techniques and several other obstacles. But in today's scenario, FFT Analysis plays a vital role in fault diagnosis, structural analysis and natural frequency determination of machines and structures.

The beginning of work on FFT Analyzers was in 1965 followed by the publication of a paper on the Computation of the Fourier Transform authored by Cooley and Turkey. The first model of Hewlett Packard was HP 5450, Fourier Analyzer. In 1975, Spectral Dynamics introduced SD 380 FFT Analyzer. This instrument was voluminous and was installed in a six feet high and 19 inch wide rack. It comprised of a minicomputer, CRT display, analog to digital convertor, digital to analog convertor, paper tape recorder and a teletypewriter . Also, it was bulky and costly. The cost of different makes of this series were in the range of $ 50000 to 1,00,000. Other leaders in this field were General Dynamic, Nicolet Scientific Corporation and Bruel & Kjaer.

In early 1980s, Loveland Division of HP, launched HP 3582, a compact-sized, 2–channel FFT Analyzer with zoom and frequency range of up to 20 kHz. The weight was about 55 lbs and price was $ 11000. Compared to HP and SD equipments, this was quite attractive and this model could therefore sale 4 times more compared to other models in the market. However, this model had not resulted from the development of applications but from miniaturization and cost reduction. The next phase of development was dominated by the applications into specific areas of science and technology.

Digital vibration control was one of the most important contributions of FFT Analysis. A vibrating shaker could be controlled to reproduce a vibration environment in the Lab, with a great accuracy. Simulation of random vibrations of a moving vehicle or railway train or periodic vibration of speeding machineries or shocks experienced by transformer bushings during an earthquake could all be possible. Digital vibration control resulted in improvements in accuracy and speed over the earlier analog systems with bank of parallel filters.

Another application was in the field of signature / spectrum analysis of rotating machineries. Identification of fault due to structural resonance or due to rotating masses became possible. Machine run-ups and coast downs could be recorded and waterfall plots could also be taken. The machinery fault – diagnosis became easier and convenient. The most popular application was however in the field of

Modal Testing. With this application, it became possible to find out the mode – shapes of different components at their natural frequencies. This was earlier achieved through cumbersome testing procedure using several individual units for excitation and for picking the vibration signal. During Mid- eighties, Bruel & Kjear introduced. Type 2032 FFT Analyzer for signature analysis as well as for modal study. The pioneers in the field were HP, GenRad, Scientific Atlanta (Spectral Dynamics), Nicolet Scientific Corp., Bruel & Kjear and LMS.

In 1990's FFT Analyzers were using Personal Computers. A card could be plugged on a PC and used as an FFT Analyzer. Digital Signal Processor chips used with FFT Analyzer were able to perform a 1024 point FFT in less than 10 msec. During this time, the main considerations were to reduce the weight for better portability and reduce the cost for increased affordability and application in industry.

Last ten years have seen modular multi – channel FFT Analyzers with real time bandwidths as high as 100 kHz and dynamic range of 120 dB. No. of channels is also not limited and measurement at several location is simultaneously possible. Earlier the connectivity was through Rs 232 and IEEE 488 interfaces. Now it is available through a number of ports viz. USB and Fire Work etc.

9. Condition Based Monitoring

After the evolution of vibration analyzers, Companies initiated periodic but manual condition monitoring and measurements. At fixed intervals of time, usually a team of two persons will record the vibration amplitude and corresponding frequency. The frequency of taking measurements could be weekly, monthly or quarterly. After few years, the manual condition monitoring was replaced, & it became possible to use recorders having rolls of paper to last for several weeks and record the signal on continuous basis. Fromhis point onwards, the concept of preventive maintenance came into existence and vibration amplitude with corresponding frequency became a major tool to pin–point the cause of high vibrations. In the early stage, data monitors were used along-with velocity transducers. The limitation of velocity transducers was that measurement in a limited frequency range only was possible, e.g., the velocity transducer model 544 of IRD Mech-analysis could measure from 12Hz only. So, low frequency measurements below 12 Hz, as required in hydro machines could not be done. Similarly, the higher frequency range was 1500Hz. But in case of fault associated with gearbox, fan blades and turbine rotors, higher frequencies were also present, which could not be measured. In 1980s, Bently Nevada brought their initial version of ADRE for continuous monitoring using accelerometers covering wide frequency range. Subsequently, several other companies also brought their instruments for a wider frequency range. By this time, the shaft vibration measurements also came into existence. 1980s and 1990s have been an era of shaft vibration monitoring using non-contact type of eddy current shaft probes. Bently Nevada kept on doing modification with their ADRE system and today their improved version is ADRE 408, which is capable of monitoring wide spectrum vibration as well as noise level. All leading instrument manufacturers included these equipments in their range of supply. Condition Monitoring is now an essential feature for monitoring of vibration data for all rotating machines specially in Power Plants and large industrial set-ups.

Fig.10: ADRE 408 of Bently Nevada

Conclusions

In last 50 years or so, we have come a long way from sensing vibration severity by placing a coin on the machine to recording an FFT for immediate fault diagnosis. In near future, it may so happen that anybody may record an FFT signal on his mobile for study of vibration behavior of machines. FFT analysis and Condition Based Monitoring, if used diligently, can save a lot of lost hours. But in-spite of available knowledge today, only a few of the Organizations seem to be serious enough to use the technology to their advantage. There is a strong need in Industries to grow dedicated experts who can devote themselves to continuously study the latest developments, make experiments, and establish better methods of fault diagnosis. Equipment technology will continue to grow but will not be able to replace the experience. The expertise obtained through experience and use of latest instrumentation will decide the effectiveness of a fault diagnosis program for resolving vibration problems.

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Bruel & Kjaer, Denmark make Tunable Band Pass Filter Type 1621.

IRD Mechanalysis, USA make Vibration Analyzer Model 345.

IRD Mechanalysis, USA make Portable Vibration Analyzer/Balancer Model 880.

Bruel & Kjaer, Denmark make Magnetic Tape Recorder Type 7006.