Proceedings of the National Seminar & Exhibition on Non-Destructive Evaluation

NDE 2009, December 10-12, 2009

Vibration Diagnostics as NDT Tool for Condition Monitoring in Power Plants

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Abstract

Vibration monitoring and analysis in rotating machineries and operating equipments gives information about anomalies developing in the system. It can identify not only specific machine faults but can also simplify repairs by identifying the root cause of the problem. Vibration signatures of a machine under load provides far more information about the internal working of the machine than any other type of electrical, infrared or other NDT testing methods. Describing the effect of damages on frequencies, mode shapes and damping, vibration test is a valuable addition to other NDT testing methods.

In this paper, the vibration monitoring and analysis case studies were presented, where vibration analysis and modification/repair done on-(a) sodium pump, a critical component in Steam Generator Test Facility, where malfunction of hydrostatic bearing was detected (b) centrifugal pump of 1200 m^3/h flow capacity used in a water test loop for circulating DM water in 1:4 scale model of Prototype Fast Breeder Reactor, where rolling element bearing failure was detected (c) Sodium pump in a 500 kW sodium loop used for various experimental studies, where bearing pedestal crack was identified. In these three cases, early identification of the impending failures not only saved maintenance cost and down time but also prevented the catastrophic failure.

1. Introduction

Periodic monitoring and maintenance in-time can save machineries from catastrophic failures. In most of the machines there will be clear indications when deterioration starts from its normal running conditions. These faults if not realized/unattended may lead to damage to the entire machinery. Machinery faults can be identified by a number of symptoms but for many types of faults in the machine, it is often possible to identify an increase in mechanical vibration before other symptoms appear. Vibration is the best indicator of overall mechanical condition and the earliest indicator of developing defects [1]. Therefore, the crux of our condition monitoring program is to periodically measure overall vibration levels (Level 1 monitoring) for assessing vibration severity and trend the values. As and when there is an appreciable increase in the vibration level, vibration spectral analysis is resorted to (Level 2 monitoring) [2] for identifying the causes of the abnormal vibratory behavior of the machine. In this paper, the vibration monitoring and analysis case studies were presented, where vibration analysis has been used to assess the health of machines that were running in real operating conditions. The impending failures of the machines were determined in its early stage by the spectral analysis method.

2. Case Study-1 Vibration diagnostics of Vertical Sodium Pump

2.1 Introduction and Description

Steam Generator Test Facility (SGTF) is a 5.5 MWt facility for testing sodium heated once through Steam Generator module at typical feed water flow of 10.5 m^3/h with pressure and temperature conditions of 172 bar & 493^{o}C. The Steam Generator (SG) has an associated sodium system. One of the key components of the sodium system is the vertical sodium pump (VSP), which circulates sodium in the main loop. Sodium at 355^{o}C is pumped through the fire heater where it is heated to 525^{o}C. This hot sodium after passing through surge tank enters the SG at the top, passes through the shell side, where it transfers heat to the steam/water in the tube side and comes out from SG bottom at 355^{o}C. The cooler sodium at 355^{o}C passes through the buffer tank and finally enters the suction side of pump. Since the availability of this pump is crucial for the sodium system in SGTF, a vibration condition monitoring program is put in place for assessing the health of the VSP periodically and to take necessary corrective actions as and when necessary, to maximize its uptime.

Table 1 tabulates the design details of the VSP. It is a vertical shaft, free sodium level centrifugal pump with double

Table 1 : Design details of Sodium Pump

Item	*Description*
Type	Centrifugal pump
Shaft	Vertical shaft
Operating Flow	105 m^3/h
Head	50 m of sodium column
Tested speed	3200 RPM
Critical Speed	3848 RPM
Bottom bearing	Hydrostatic Bearing
Top bearing	Ball bearing
Seal	Double mechanical seal
Seal oil cooling	Forced oil cooling
Seal oil flow rate	23 litres/minute
Seal oil temperature	< 50°C
Design pressure	1.93 kg/cm^2 (g)
Design temperature	525°C

mechanical seal at the top and hydrostatic bearing at the bottom. It can deliver 105.5 m^3/h at 50 m sodium column at speed of 3100 RPM. The drive is a 37 kW variable speed motor. Considering the pump vibration problems, the speed is limited to 3200 RPM. Figure 1 shows the pump assembly. Vibration measurements were carried out on Motor Drive End, Motor Non-Drive End, Lantern, Pump outer vessel locations etc periodically. These locations conform to ISO 10816-1:1995 standard for Mechanical vibration - Evaluation of machine vibration measurements on non-rotating parts. In addition, to assess the condition of the rotating parts, viz. the impeller and hydrostatic bearing, an acoustic SS rod has been welded to the discharge casing and an accelerometer mounted on the cold end (<100°C). Accelerometer signals are conditioned and fed to an analyzer for time domain and frequency domain analysis [3]. As the pump was running smooth the vibration value was less than 1 mm/s and during the continuous operation of the pump an increase in vibration velocity value of 5.05 mm/s was observed.

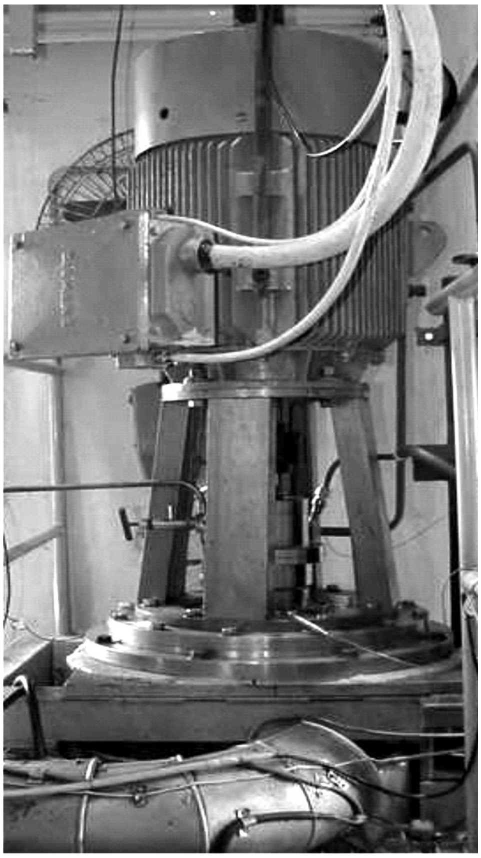

Fig. 1 : Sodium Pump Assembly

2.2 Analysis and Conclusion

Vibration spectra measurements were done on various locations on the pump and Fig. 2 shows the spectra recorded at the pump discharge location for 1500 RPM. It is inferred from the spectra that a well prominent peak at 65 % of the running speed is occurring at 1500 RPM.

The sub harmonic peak could be due to oil whirl or oil whip [4]. But since there is no relative motion between the sodium film in contact with the rotor in the case of hydrostatic bearing, these causes were ruled out. So the presence of sub harmonic peaks was attributed to rotor rub with some mechanical looseness. Time signal plots (Fig. 3) recorded during the operation supported the occurrence of intermittent rubbing/hitting of the rotor. Moreover the vibration levels were maximum at the discharge location and found to be increased with increase in running RPM. Based

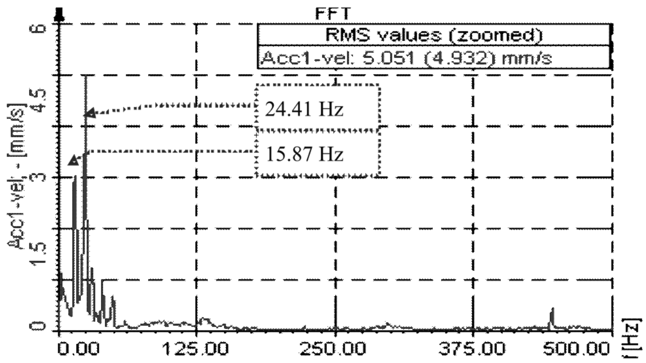

Fig. 2 : Vibration Spectra

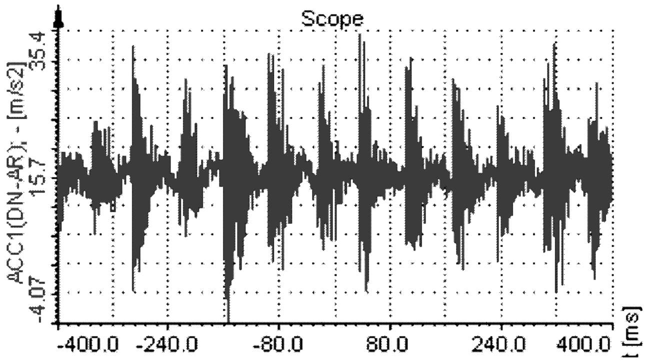

Fig. 3 : Vibration Time Signal

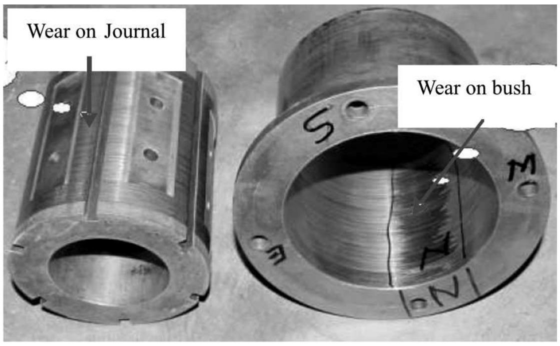

Fig. 4 : Bearing components

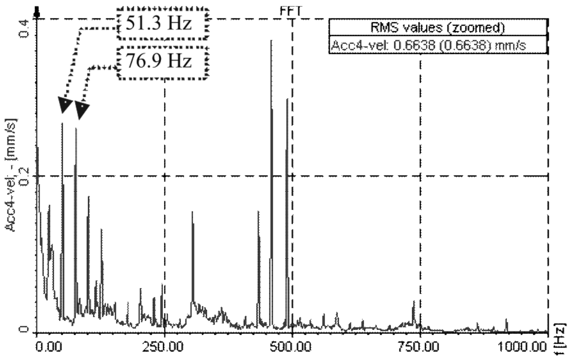

Fig. 5 : Vibration spectra

on the analysis shutdown of the pump was planned to inspect the pump internals by removing the pump assembly from the vessel.

After dismantling the pump, it was found that hydrostatic bearing was damaged and the journal had worn out (shown in Fig. 4). To determine the cause of this rub, an analysis was carried out and it emerged that the suction line of the pump was not flexible enough to accommodate the thermal expansion due to which the pump assembly as a whole was moving by as much as 1000 microns, against the radial clearance of 110 microns between the journal and bush of the hydrostatic bearing, which was causing the rotor rub [5]. To improve the flexibility, an expansion bend (U-bend) was introduced in the suction line of the pump. Also, the pump vessel was aligned vertically and a guide in the labyrinth area, at the bottom, was provided to arrest the lateral movement of the pump vessel. After the corrections, the deflection of the pump vessel reduced to 13 microns, well below the 110 micron limit. The overall vibration came down appreciably to 0.66 mm/s (Fig.5) compared to 5.05 mm/s earlier. Thus an effective vibration based condition monitoring program has resulted in considerable savings by identifying the system design fault in its early stage of operation and prevented any catastrophic damage to the vertical sodium pump internals.

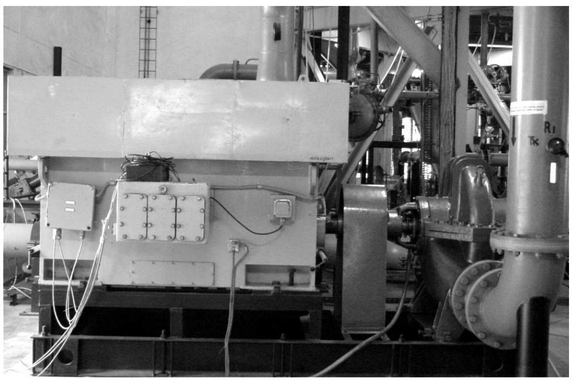

Fig. 6 : 510 kW Pump-Motor Assembly

3. Case Study-2 Vibration diagnostics of Centrifugal pump of 1200m^3/h capacity

3.1 Introduction and Description

The ¼ scale model of Prototype Fast Breeder Reactor (PFBR) assembly, named SAMRAT (Scaled Model of Reactor Assembly for Thermal hydraulics), has been designed and commissioned in IGCAR for studying the thermal hydraulics and vibration characteristics of the primary reactor components. A water test loop is used to circulate water through this model for conducting various experiments. Six centrifugal pumps of varying capacities are used for circulating water in the model, for simulating different flow similitude requirements for various experimental studies. One of the large capacity pumps in this loop is of 1200 m^3/h flow and 100 mlc head capacity (Fig.6). This is a single stage horizontally mounted centrifugal pump driven directly by a 510 kW induction motor. The description and features of the pump is highlighted in Table 2.

Vibration measurements were carried out during the pump operation in three axes (horizontal, vertical and axial) on motor and pump at the drive end and non-drive end bearing locations as well as on the foundation pedestal. Development of an abnormality was detected during one such measurement which indicated an increase in overall vibration level from 1.5 mm/s to 5.5 and 6.3 mm/s on pump drive end (DE) bearing locations in horizontal and vertical directions respectively, where as in the non drive end (NDE) location, it was high in vertical direction only (5.9 mm/s). The vibration values observed at other locations were well within the limits (as per the ISO-10816-2 limits for a Class-III machine). So it was decided to monitor the pump operation closely for the next two runs. In the measurements taken subsequently, the pump DE bearing vibration increased to 7.0 and 8.0 mm/s in horizontal and vertical directions

Table 2 : Design details of Pump

Item	*Description*
Type	Centrifugal pump
Head	100 m
Capacity	1200 m^3/h
Motor Power	510 kW
Speed	1488 RPM
Suction/Delivery	300 / 250 mm
Motor make	Kirloskar
Pump Bearing	Ball bearing SKF 6218

respectively whereas in the pump NDE bearing location, vibration values not varied much. In subsequent runs, the vibration values in both pump DE and NDE bearing locations shot up to 8.4 and 9.2 mm/s. So vibration spectral analysis was carried out to identify the underlying causes for the abnormal pump vibration characteristics.

3.2 Analysis and Conclusion

Figure 7 shows a vibration spectra recorded from the pump drive end location in vertical direction. All the spectra indicated 1 x RPM and 5 x RPM peaks as predominant in the radial directions without many harmonics. This lead to the conclusion that the underlying problem is an unbalance type, but the cause of the unbalance was not clear. The 5 x RPM component led to the understanding that it could be Pump drive end bearing deterioration or problems with the vanes of the impeller since 5 x RPM lies in the range of bearing defect frequencies (1), which are calculated below and more over the 5 x RPM corresponds to the vane passing frequency (VPF) (Since impeller is having 5 vanes).

BPFI = 0.6 x RPM x n = 0.6 x 10 x RPM = 6 x RPM and
BPFO = 0.4 x RPM x n = 0.4 x 10 x RPM = 4 x RPM

where, n=number of balls in the bearing (=10)

So, it was decided to inspect the pump internals for defects and damages and the pump was shutdown for maintenance. Upon disassembly it was found that the pump DE bearing outer race has worn out and the DE gun metal sleeve was having a running hair crack (Fig.8). This transverse crack in the sleeve was causing unbalance in the pump assembly. The unbalance has led to eccentricity in the impeller rotation which is getting reflected as the 5 x RPM component in the spectrum, corresponding to the VPF. As regards the pump DE bearing, the unbalance is causing the bearing to stress out due to uneven loading and resulting in wearing of the outer-race. During the corrective maintenance, the gun metal sleeve and drive end bearing was replaced and pump was re-assembled. Vibration level was also found to be reduced to 1.45 mm/s (Fig.9). Thus vibration analysis was used to detect the abnormality at an earlier stage, otherwise which could have resulted in damage to the shaft and other pump/motor internals.

4. Case Study-3 Vibration diagnostics on Sodium pump

4.1 Introduction and Description

A 500 kW Sodium Loop (Fig.10) is designed and constructed in IGCAR to get experience in handling large and high temperature experimental sodium loop and also to test the performance of sodium pumps and other indigenously developed components, designed for various applications in reactors. Sodium is circulated in the loop by a 100 m^3/h vertical centrifugal pump, which is installed in the cold leg of the loop. The centrifugal pump takes suction from

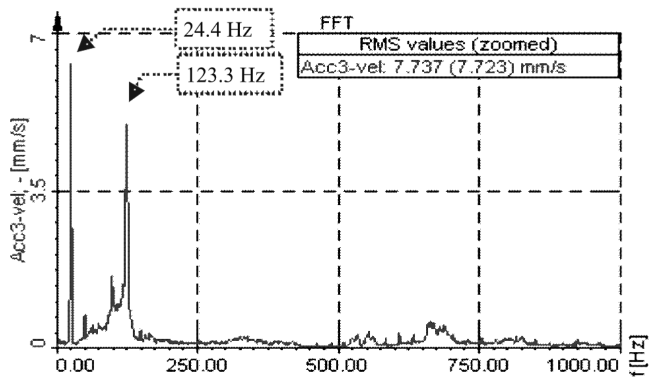

Fig. 7 : Vibration Spectra

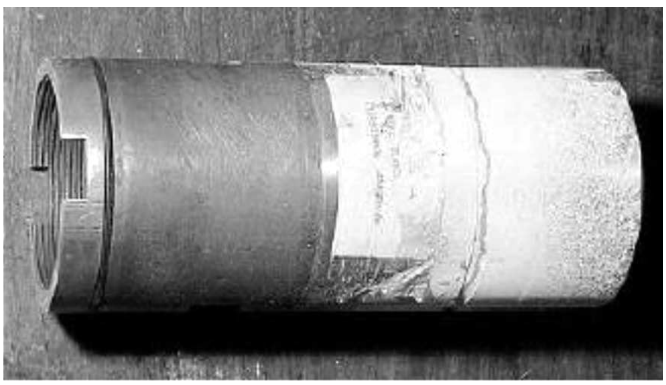

Fig. 9 : Vibration spectra

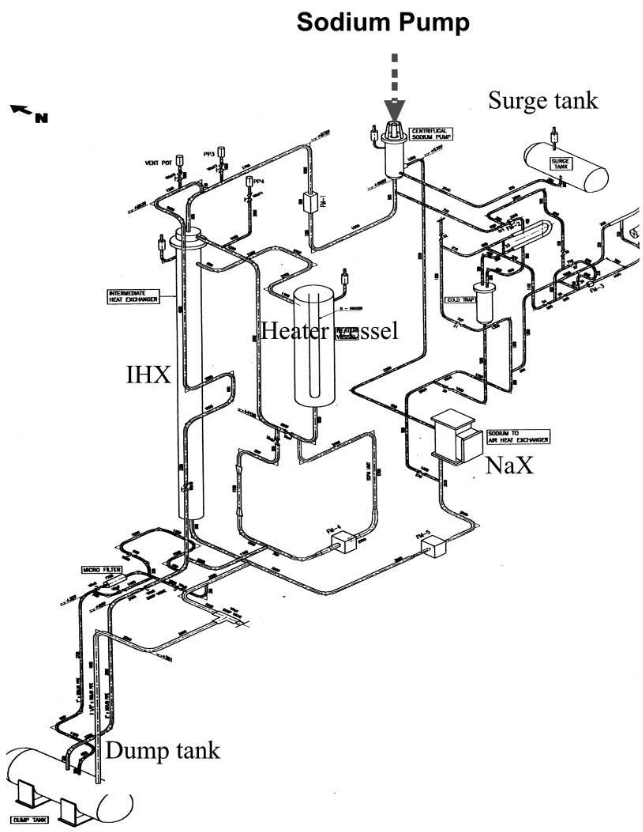

Fig. 10 : 500kW Sodium Loop

Sodium-to-Air heat exchanger (NaX) and forces cold sodium into the tube side of the Intermediate Heat Exchanger (IHX). Being an important component of the 500 kW Sodium Loop, the performance of the sodium pump has to be checked frequently. Hence vibration measurements were carried out on different locations of the pump at periodic intervals. The description and main features of the sodium pump are given in Table 3. The pump has a vertical shaft which is driven by a variable speed DC motor.

Table 3 : Design details of Pump

Item	*Description*
Design Basis	ASME Section – VIII, DIV-I
Design Pressure	4 kg/cm^2
Design Temp.	425°C
Type	Vertical Shaft,Free Sodium level Centrifugal PumpDouble Mechanical Seal and Hydrostatic Bearing
Rating	Capacity- 100 m^3 / h; Head- 22.5 m Speed- 2900 rpm; NPSHR- 3m
Drive	SCR controlled variable speed (1500 – 3000 rpm) DC motor of 30 HP
Cooling	Forced Oil circulation24 l/h by Rotary Gear Pump
Oil Temperature	50°C- Oil in turn cooled by Air Cooler

Accelerometers were installed on various critical locations on the pump such as motor bearing locations, pump vessel flange, mechanical seal etc. apart from this, periodic vibration measurements were also done on other areas such as lantern, pump inlet/outlet locations etc to assess the health and to ensure the smooth running of the pump. As the pump was running very smooth, overall vibration values were less (2 mm/s) and within the limit. The loop was under continuous operation and various experiments were carried out during the test campaign. In the due course of operation, a sudden increase in the vibration value was observed while the pump was running at around 2000 RPM. The value shot up suddenly crossing the pre-warning level of 2.8 mm/s, set as the threshold level with reference to the standard ISO-2372 for a class-II machine. Subsequently, the overall RMS velocity value at the motor side crossed 5 mm/s.

4.2 Analysis and Conclusion

Using hand held vibration analyzer, over all RMS value was taken at different locations on the pump and motor and a high value of vibration was observed on the motor. Even though the vibration levels at various parts of the pump got increased, it was clear from the over all vibration measurement that, the high value at the motor side only got reflected at other locations. Vibration spectra were taken on the motor for observing and interpreting the abnormality. In radial and axial direction, vibration spectra were recorded from the drive-end and non-drive end of the sodium pump. Vibration value at the motor non-drive end radial direction was 5.4 mm/s

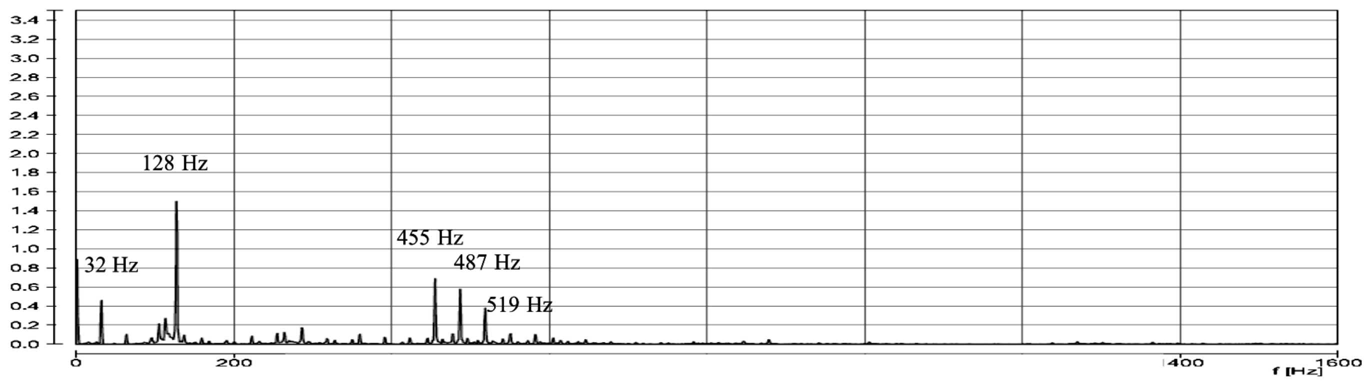

Fig. 11 : Vibration spectra during fault development

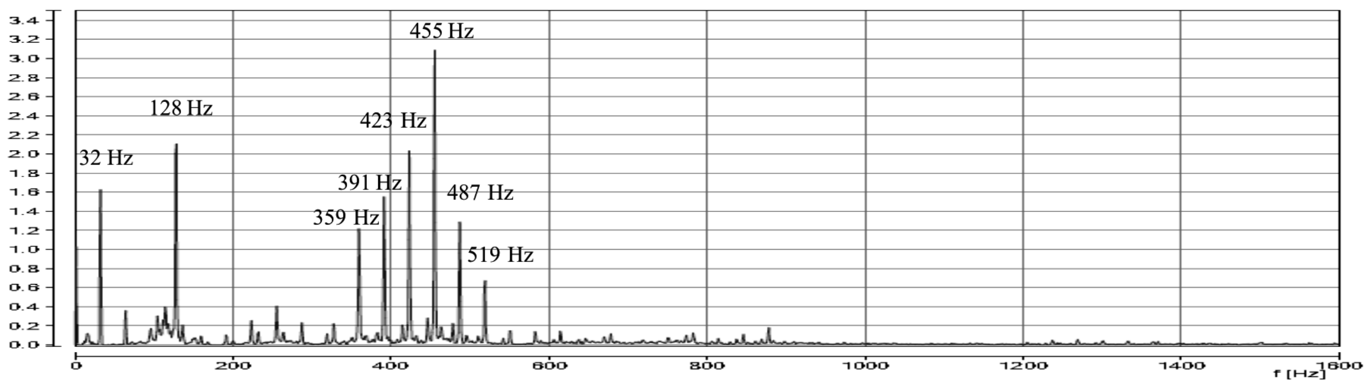

Fig. 12 : Vibration spectra (RMS value 5.4 mm/s)

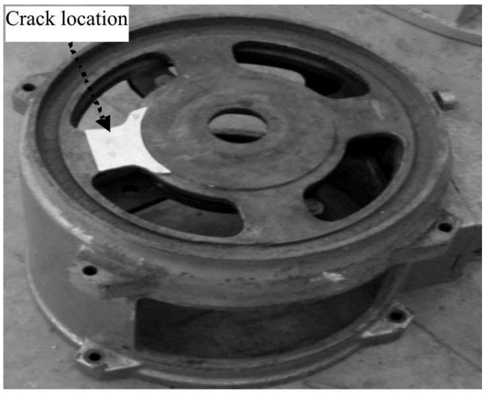

Fig. 13 : Bearing support block

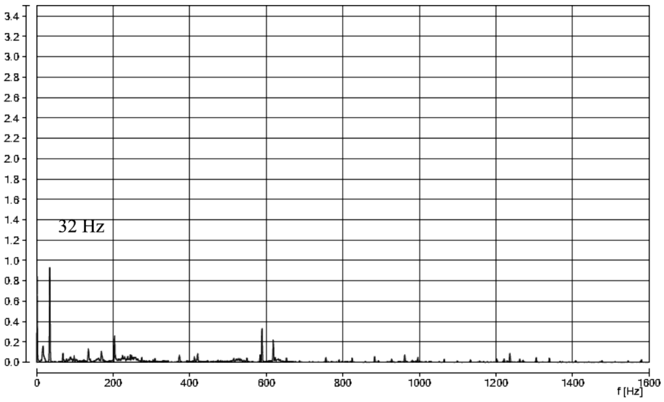

Fig. 14 : Spectra after reinforcement

whereas the axial vibration value was 2.25 mm/s only. Fig.11 shows the vibration spectra taken from the motor non-drive end in radial direction during the development of the fault and Fig.12 shows the vibration spectra when the vibration value reached 5.4 mm/s. In Fig.11 the predominant frequency component is 128 Hz. The motor non-drive end uses SKF 6309 anti-friction bearing and for the current running speed, 128 Hz corresponds to the ball spin frequency of the bearing. The frequency components observed in Fig.12 is complex in nature showing multiple peaks spreaded over the entire spectra. Apart from the ball spin frequency, around 400 Hz multiple spectral peaks of nearly the harmonics of BPFO and BPFI of the bearing were observed and were found to be at exact intervals of the running frequency 32 Hz. So it was concluded that the ball spin frequency peak was the first indication followed by the development of bearing tones confirms the fault with bearing/bearing support system [6].

Pump shutdown was scheduled and inspection was carried out at the motor non-drive end bearing location. A developed crack has been observed on the motor non-drive end bearing support block. Fig.13 shows the location of the crack. As the pump was required for various sodium loop experiments, the cracked location was reinforced with aluminium plates (Fig.13) and the pump has been brought back into service. After the maintenance the vibration values were found to be well within the limit and Fig.14 shows the corresponding vibration spectra.

Conclusions

Vibration analysis as an NDT tool, enables the easiest and earliest detection and identification of abnormalities in running machineries. The combined application of experimental and computational vibration analysis is well suited for characterizing the changes in properties of materials, especially when caused by structural damages. Vibration signatures of a machine under load provides far more information about the internal working of the machine than any other type of electrical, infrared or other NDT testing methods. Describing the effect of damages on frequencies, mode shapes and damping, vibration test is a valuable addition to other NDT testing methods. Vibration measurements and analysis also enables the scheduled shut down of the running plant for inspection and maintenance, there by effectively reducing the down time of the plant. Vibration analysis offers the highest level of predictive maintenance available which stands in sharp contrast to 'run to failure' method of maintenance.

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