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Condition monitoring of reciprocating air compressor using vibration and noise control techniques for better NVH

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Abstract. The major problems experienced in reciprocating air compressor are excessive noise in operation and vibration of the compressor. In this paper a reciprocating air compressor is studied and it is monitored to find the mechanical or other faults present in it by performing noise and vibration test. Here vibration signature analysis is done along with measurement of noise harshness level of a reciprocating compressor. After the test the faulty part of the compressor was replaced and same test was performed again. Microscopic analysis of parts of bearings was also done to study and analyze the cause of defects. Here significant improvement is achieved in NVH.

1. Introduction-

Condition Monitoring (CM) is a maintenance technique in which the health and condition of different parts of machines, equipments and systems are checked by monitoring and measuring some signals and variables. The detection and correction of faults in systems like compressors is used subsequently in research field to minimize the cost of maintenance and apply methods of improved condition monitoring [1]. The fault diagnosis in a reciprocating compressor which decays the performance of compressors is also used to increase the performance of plants [2].

Some works have been done to improve the working condition and detection of faults by condition monitoring technique. Jitendra Kumar Sasmal [3] used a technique based on vibration data and merging process with the motive of developing the detection of mechanical faults in industrial systems subjected to variable load conditions. Yuefei Wang [4] found out a mathematical model using MATLAB for predictive condition monitoring. In his work, five properties were described like speed- torque characteristics of an induction motor, rotation of crankshaft, valve plate vibration, variation of pressure of a cylinder and flow characteristics through a valve. R. C. Singh [5] suggested certain preventive maintenance methods for condition monitoring of air compressor. Various condition monitoring techniques like vibration monitoring, sound monitoring, corrosion monitoring using thermograph, performance and behavior monitoring, debris monitoring, etc. were described in this paper.

Some work related to vibration has been carried out by many researchers in the past. Mathias Neumann [6] did vibration analysis on a transonic compressor to find out blade tip clearance and blade vibration. He used Laser Doppler Distance Sensor (LDDS) to find out expansion of radial blade, the deflection of circumferential blade and circumferential velocities of the blade tip of rotor. Vibration frequencies and amplitude were calculated in this paper. C. Ruiz-Carcel [1] determined mechanical faults in systems by analyzing signature of vibration signal which was found in time and frequency domain. Zengli Wang [7] did work on flexural vibration, torsional vibration and longitudinal vibration to find out the natural frequency of rotor journal bearing system with change in speed.

The electrical motor present in air compressor can be subjected to vibration under varying load condition [8-11]. It freely vibrates at its own natural frequency or forced at different frequencies. The vibration produced can give the information of state of a compressor also vibration monitoring is an important technique for condition monitoring of electrical motor.

The defects in the bearings present in the air compressor are caused by surface roughness, waviness, misaligned races and off-size rolling element [12]. Roller element bearings fail due to fatigue stress giving rise to pitting, flaking or spalling [13], heat production due to inappropriate fitting or over greasing or cage fracture due to poor fitting and surface distortion due to wrong lubrication and over load. The heat generated in a bearing due to friction is caused by external loads, type of lubrication, rotational speed and coefficient of friction [14-16]. A repeated vibration is produced due to defects in roller elements bearings. Such vibration are of very low amplitudes so with overall vibration monitoring, it gets embedded in rotational machine vibration signals. Bearing faults results in a periodic train of impulse excitation [17]. A continuous and repetitive frequency is produced due to defects in inner race, outer race and rolling element bearings.

2. Experimental Analysis

2.1 Experimental Setup

The experiment was set up in the lab and it comprised of useful devices which can be used for condition monitoring, vibration signature analysis and noise detection and readings.

Figure 1. The experimental setup with condition monitoring equipments.

The equipments that are used for performing the experiments are as follows:

(i) A reciprocating air compressor: Type- Single cylinder, reciprocating, Weight- 42 kg, Maximum capacity- 60 m^3/hr, Maximum pressure- 300000 kg/ m^2.

(ii) Sophisticated accelerometer or sensor: Type- Single axis accelerometer (SQ 1608AN), Sensitivity- (±15%) 100 mv/g (10.2 mv/ (m/s^2)), Frequency range- (±3 db) 30 to 600000cpm (0.5 to 10000 Hz), Measurement range- ±50g (±490m/s^2), Electric Connection- 10 cable to CBN connector.

(iii) FFT analyzer: OROS -3 series/ NV gate, 4 channel type, Hardware- OR 34 system.

(iv) Noise level meter: Parameter measured: Lp, Lmax, Leq, Ln, Measurement range: 30-130 db (A), 35-103 db (C), 35-130 db (F), Resolution- 0.1 db, Accuracy- ±1 db, Frequency- 20 to 12500 Hz, Alarm value set- 30-130 db.

(v) Microscope: Olympus STM6 measuring microscope, Software for analysis is Olympus stream basis, Objective lens (3X, 5X, 10X, 20X), Eye piece (10X) fixed.
(vi) Laptop/computer for recording the readings.

2.2 Experimental procedure

All the devices mentioned above were taken and connected with each other to perform the experiment. At first the reciprocating air compressor was taken for condition monitoring. The accelerometer was connected to the FFT analyzer and similarly the analyzer was connected to the laptop for recording and analyzing vibration signal. The accelerometer was connected to the compressor at various points by a strong adhesive (fevi quick gum) to ensure perfect and tight surface to surface contact. The sequences of experimental procedures are as follows:

Collection of measurement data, Measurement and analysis of frequencies, Microscopic test of balls of bearing, Noise testing of compressor

3. Results and Discussion

3.1 Calculation of Bearing Frequency and Vibration Signature (theoretical)

The specification of the motor bearing of the air compressor was as follows:

Number of balls (n) =8, Ball Diameter (d) =6mm, Pitch Diameter (D) =29mm, Angle of contact (β)= 23.56^0, Rotational Speed (N_r) =1425mm.

Ball pass frequency of outer race (BPFO) = $\frac{n}{2} \times \frac{Nr}{60}[1-\frac{d}{D}Cos\beta]$=73.983Hz

Ball pass frequency of inner race (BPFI) = $\frac{n}{2} \times \frac{Nr}{60}\left[1+\frac{d}{D}\,Cos\beta\right] = 113.017\;Hz$

Ball spin frequency/ rolling element frequency (BSF) = $\frac{D}{d} \times \frac{Nr}{60}[1-\left(\frac{d}{D}\right)^2 \mathrm{Cos}^2\,\beta]$ =110.663 Hz

Fundamental train frequency (FTF) = $\frac{1}{2} \times \frac{Nr}{60}\left[1-\left(\frac{d}{D}\right)Cos\,\beta\right] = 9.623Hz$

3.2 Calculation of Bearing Frequency and Vibration Signature (experimental)

Vibration signature analysis was done by using the initial bearing attached to the compressor first and then by replacing the bearing with a new one. The vibration signature of motor having damaged and good bearing is:

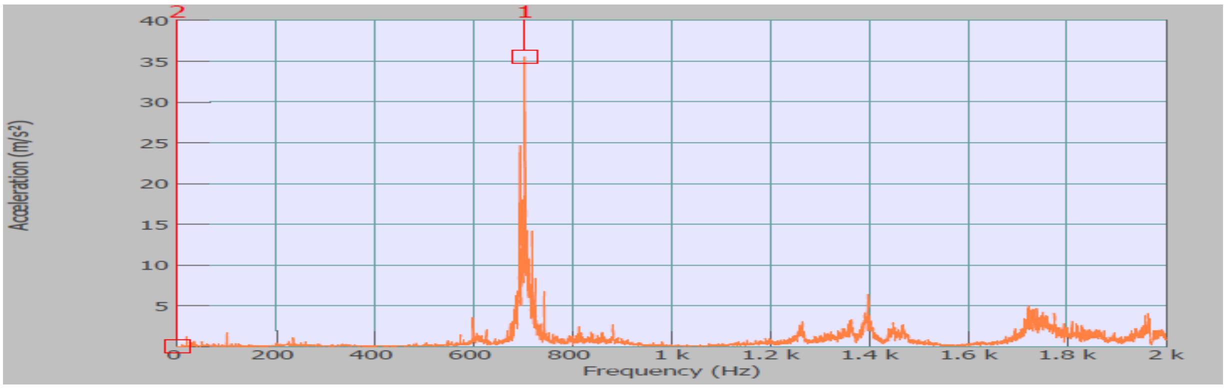

Figure 2. Vibration Signature of Damage Bearing.

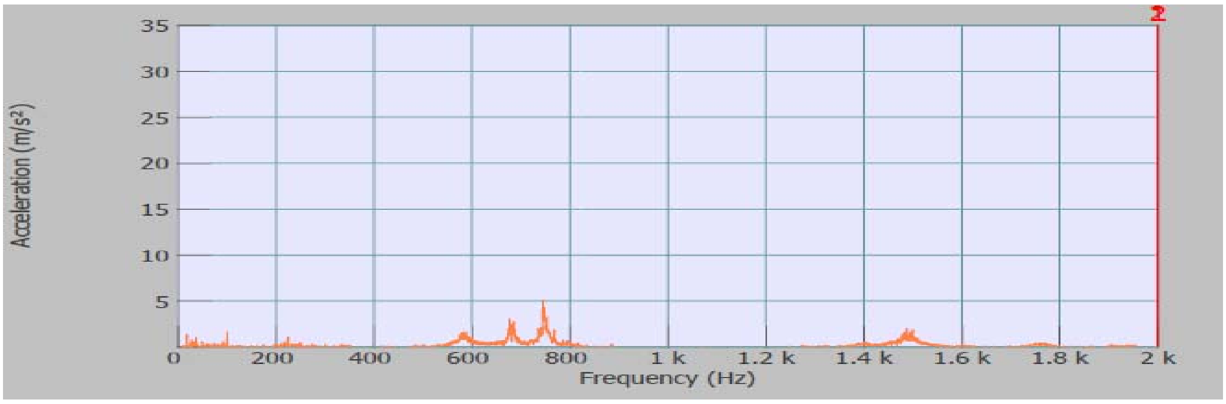

Figure 3. Vibration Signature of Good Bearing.

3.3 Defect analysis of Balls of Bearings present in the motor under Microscope

The bearing was dismantled and tested under the microscope. Here are some of the results of the microscopic view of the damaged and good bearing balls.

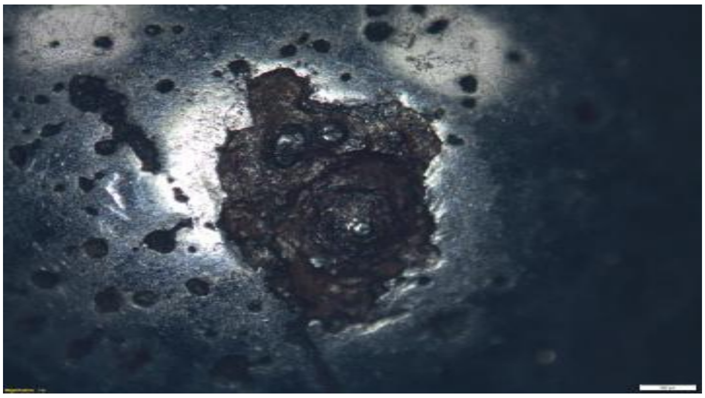

Figure 4. Ball of damaged Bearing under microscope (5X magnification).

Figure 5. Ball of good Bearing under microscope (5X magnification).

3.4 Noise Harshness Test on Motor of Compressor by using Noise Level Meter

The noise reading of the motor with the defected and good bearing are shown in the figure below.

Figure 6. Noise test on the motor with Damaged Bearing.

Figure 7. Noise test on the motor with good Bearing.

The average noise level with defected bearing was found to be 101.0 db whereas the average noise level with good bearing was found to be 87.6 db. So the noise level was reduced and at least the noise produced from the motor was brought close to below permanent threshold shift or permanent hearing loss which is anything above 90 db.

4. CONCLUSION

By this paper we studied a simple method to detect noise and vibration signature of a reciprocating air compressor. It was found out from the experiment that the air compressor was producing a lot of noise. The faulty part in the compressor which was the roller bearing was detected and faults present in was studied. The vibration frequency was calculated both theoretically and experimentally and the signature was plotted in acceleration vs. frequency graph. The graph shows very high acceleration results which proved abnormal vibration signature in the motor with faulty bearing.

It was found out from this paper that the compressor produced a lot of noise which was above the level which can be tolerated by human ear. A minor cause of vibration was the nut on the pulley which acted as an unbalance mass which was changed. There was fault in bearing of the motor which was the major cause of the vibrations and the noise coming out of the motor. The highest noise level of the motor was found to be 101 db which was from the back side of the motor. The reasons for bearing failure was also studied and compared with the results we got under the microscope. By replacing the bearing of the motor, a lower acceleration range was noted in the vibration signature plot, and the noise level was also reduced which was found out to be 87.6 db maximum.

Thus, the condition monitoring of the reciprocating air compressor by noise and vibration test leads to identification of faulty parts. After replacement of the faulty parts, the compressor could run in condition which gave better NVH.

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