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Investigation of Mechanical Faults in Rotating Machines Using Condition Monitoring Tool

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Abstract: *Rotor unbalance is the most common cause of vibration in rotating machinery. Excessive unbalance can lead to fatigue of machine components, as well as can cause wear in bearings or internal rubs that can damage seals and degrade machine performance. The condition monitoring has become an effective strategy to reduce the maintenance cost and improve the availability of systems. In this paper, unbalance effect is investigated experimentally in forward curved centrifugal blower test setup with coast down time (CDT) as a condition monitoring parameter. For this, the tests were conducted for different cases of unbalance by introducing additional mass and coast down time recorded at cut-off speeds of 1000 rpm, 1500 rpm, 2000 rpm and 2500 rpm respectively. The CDT profiles for different unbalance masses at various cut-off speeds are investigated. The vibration spectrums for different unbalance conditions are studied and compared with CDT. The results show that with increase in unbalance mass the Coast Down Time decreases in comparison to the baseline CDT. As unbalance mass increases, the blower shaft comes to rest faster (with less time). The CDT reduction percentage increases as unbalance mass increases. The 1X vibration amplitude component increases as the unbalance mass and shaft rotational speed increases, thereby establishing the fact that the CDT analysis can be used as one of the diagnostic condition monitoring parameter for rotating machinery.*

Keywords: *Condition Monitoring, Rotating Machinery, Unbalance, Coast Down Time,*

1. INTRODUCTION

Availability of the machines can be increased through condition based maintenance (CBM), by monitoring diagnostic parameters such as vibration, noise etc. Rotor unbalance is the most common of system malfunctions and is the cause of vibration in machinery. Unbalance is the non-uniform distribution of the mass of an assembly about its axis of rotation. It damages machinery by imposing cyclic forces on bearings and shaft that lead to fatigue failure. Their primary symptom is 1X (1*rotational speed) vibration amplitude, which, when excessive, can lead to fatigue of machine components. In extreme cases, it can cause wear in bearing or internal rub that can damage seals and degrade the machine performance [1]. Mechanical damage and contaminant build up are the two main causes of unbalance in fans. Unbalance in impeller is due to mechanical damage and corrosion. Condition monitoring involves detection, diagnosis and prognosis of all rotating machinery components for their malfunctions such as imbalances and misalignments, fractures, contaminations etc., which would result in loss of production and also unwanted breakdown. The condition monitoring (CM) or condition based maintenance has become an effective strategy to reduce the maintenance cost and improve the availability of systems. This has largely been successful due to the simultaneous development of objective sensors and instrumentation both for detection and analysis of faults. In short CM is comparable to health monitoring in human system [2]. Vibration monitoring has proved to be a very effective monitoring technique. Vibration signatures are widely used as a useful tool for studying progressive machine malfunctions particularly unbalance, and also form the baseline signature for further comparative monitoring to detect mechanical faults [3]. It is estimated that nearly 70% of the machine failures can be identified from their spectrums similar to the ECG in medical diagnostics.

Various condition monitoring techniques were exploring by many researchers, Coast Down Phenomenon (CDP) during deceleration period in particularly has attracted enormous attention. One of the important tools, namely Coast Down Time (CDT) has come into prominence in the last few decades. In this work coast down time is used as a diagnostic parameter to detect and analyse the effects of rotor unbalance of industrial machinery in service at initial stages. When the power supply to any rotating system is cut-off, the system begins to lose the momentum gained during sustained operation and finally comes to a halt. The behavior of the rotor system during this period is known as the coast down phenomenon (CDP). The exact time period between the power cut-off time and the time at which the rotor stops is called Coast Down Time [4]. The CDT is the total time taken by the system to dissipate the momentum acquired during sustained operation. An extensive investigation conducted on vertical rotors supported by rolling element bearings, established that CDT monitoring could be used as a health monitoring, quality control and maintenance tool [5]. The CDP is inherent of a system and the CDT depends on many factors like inertia forces of the system components, tribological behavior of rotating system components such as bearings, seals, carbon brushes; it also depends on operating conditions and environmental effects such as fluid drag. Some work published have reported experiments conducted on rotor system to evaluate the bearing lubrication for different operating conditions and the influence of the rotor unbalance response on CDT, in which it was found that CDT could be used as an effective diagnostic parameter and could provide pertinent information regarding the tribological behavior, degradation and the effectiveness of lubrication [6]. A mathematic model is developed [7] to study dynamic characteristics of unbalance. They derived generalized system equations of motion for a rotor under unbalance conditions using the finite element method. Spectral method was used for resolving the equation of motion and to obtain and analyse the dynamic response and consequently to identify unbalance fault. Much of the studies were focused on analysis of tribological behaviour of rotor systems [8]. However, the literature on the CDT analysis for considering the effect of unbalance is hardly found, which ought to be given due consideration. CDT analysis is a powerful parameter for studying the significant machine health particularly when the rotor systems are supported with bearings. It can be used as a consistent guide to assess the condition of the system. However, it has not received much attention by researchers. CDT, together with the vibration analysis, could be used as a powerful diagnostic tool for condition monitoring of rotating machineries.

All these studies were conducted on rotor system supported between two bearings. The potential of using CDT for condition monitoring has been reported but not explored in the industrial practice. The detection and diagnosis of mechanical faults in machinery through CDT as a diagnostic parameter is an area where further in depth investigations are needed. In this paper therefore an attempt is made to experimentally investigate the use of CDT analysis as one of the condition monitoring parameter on a forward curved centrifugal blower to assess the effect of unbalance for understanding the mechanical behavior of system under simulated industrial environment. Further, CDT analysis is compared with vibration signature analysis for identifying the severity of unbalance. The vibration spectrums for different unbalance conditions are presented and discussed.

2. EXPERIMENTAL SETUP AND EXPERIMENTAL PROCEDURE

An experimental Forward Curved (FC) centrifugal blower test setup [9] is used for this investigation. The photographic view of experimental test setup is shown in Figure 1. A FC centrifugal blower of 2 kg weight is mounted on shaft with length 315 mm and diameter of 20 mm at the center position of 190 mm between two anti-friction bearings. The shaft is simply supported between two antifriction ball bearings. The blower shaft is connected through an electromagnetic coupling to a variable speed DC motor shaft. The whole test setup unit is mounted on heavy steel framework, and then the framework is clamped to a massive concrete foundation isolated from the environment by anti-vibration rubber pads. Two inductive proximity sensors were used to measure the speeds of blower shaft and motor shaft independently. The Visual Basic based application software developed along with instrumentation is used to control the operation of experimental test setup and to record motor and blower speeds as well as coast down time for each test run for selected cut-off speeds. A speed controller knob is provided to vary the voltage to adjust the power supply to the motor to enable the motor speed and blower speed to be held at specific cut-off speeds for testing. During start of test run, the system automatically cuts off the power supply to motor and magnetic coupling simultaneously so that the blower shaft completely disengages from motor shaft. At the end of test, the power supply is restored for both motor and coupling such that they run continuously. The software used has the ability to record CDT with an accuracy of 0.06 seconds (60 ms) intervals.

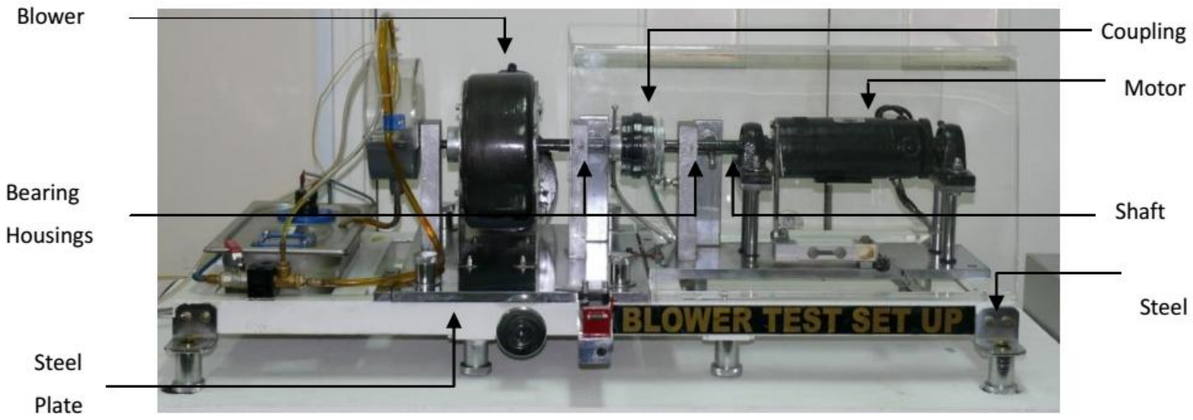

Fig1. *Forward Curved Centrifugal Blower Experimental Test Setup*

The LabVIEW7® application software model, developed for FFT analyser is used to acquire vibration signals. Three piezoelectric accelerometers were used to acquire vibration signals in vertical, horizontal and axial directions.

The blower shaft and motor shaft are carefully aligned and balanced in both vertical and horizontal directions. This aligned and balanced system is used as a reference for creating the required quantity of unbalance conditions. Initially CDTs for each test run at all the selected rotational cut-off speeds were recorded. To check for consistency the test run was repeated five times under the same operating conditions and the CDTs were recorded. Error analysis was carried out for sample size of five to verify the validity and accuracy of CDT data. The magnitude of the error is found to be less than one percent. The recorded CDTs were used as baseline reference for further investigation, analysis and comparison. The test intervals of 30 to 45 minutes have been chosen to ensure that the system attains a steady state condition and to acquire sustainable momentum. The baseline CDTs obtained for blower at cut-off speeds of 1000 rpm, 1500 rpm, 2000 rpm and 2500 rpm are 1560, 2040, 2580 and 3000 milliseconds respectively under healthy operating conditions. Vibration signatures spectrum along vertical, horizontal and axial directions at blower end shaft bearing housing were recorded under, healthy operating conditions and used thereafter as baseline references for further investigation, analysis and comparison. The experimental tests at different cut-off blower speeds i.e., 1000 rpm, 1500 rpm, 2000 rpm, and 2500 rpm respectively have been carried out to record coast down time for different unbalance conditions. The masses have been added on blower impeller blade to create unbalance and to understand the influence of unbalance on CDT. Tests were conducted for three cases of unbalance condition by introducing additional mass of 22 gram-mm, 27 gram-mm and 32 gram-mm respectively at a radial distance of 61mm from the centre of the impeller blade. All the experiments were conducted by changing the mass in the same location in the impeller blade. The maximum unbalance weight added is restricted to 32 gram-mm as per the design specifications of the manufacturer. The main objective of this study is to explore the use of CDT analysis to detect and analyse the effect of unbalance on forward curved centrifugal blower rotating machinery.

3. RESULTS AND DISCUSSIONS

The profile of the CDT curves, the speed in rpm versus CDT in milliseconds for balanced condition and various unbalance condition of different mass 22 gram-mm, 27 gram-mm and 32 gram-mm on the blower impeller blades at blower shaft cut-off speeds of 1000 rpm, 1500 rpm, 2000 rpm and 2500 rpm respectively are shown in Figure 2. The purpose of introducing the different unbalance conditions is to study the mechanical behavior of the system during these conditions at different cut-off speeds and consequently the influence on CDT values and comparing these CDT profile curves with respect to vibration spectrums. Since the blower shaft is completely free from driving shaft during coast down period, as predicted, blower shaft takes longer time to dissipate the acquired energy during sustainable operation at higher running speeds, consequently higher CDT obtained.

The CDT profile curve is typically characterized by three zones, at the beginning of the coast down a small convex shape, at the middle of the coast down a concave and at the end of the coast down a small convex shape. From the CDT profile curve it can be seen that higher energy dissipation takes place at the middle of the coast down. This is due to the fluid friction which decreases with the decrease in speed. The small convex shape at the end of the coast down is due to mixed film lubrication or boundary lubrication. In this region, metal to metal contact exists between the mating surfaces, where the resistance to movement increases with decrease in rotational speed.

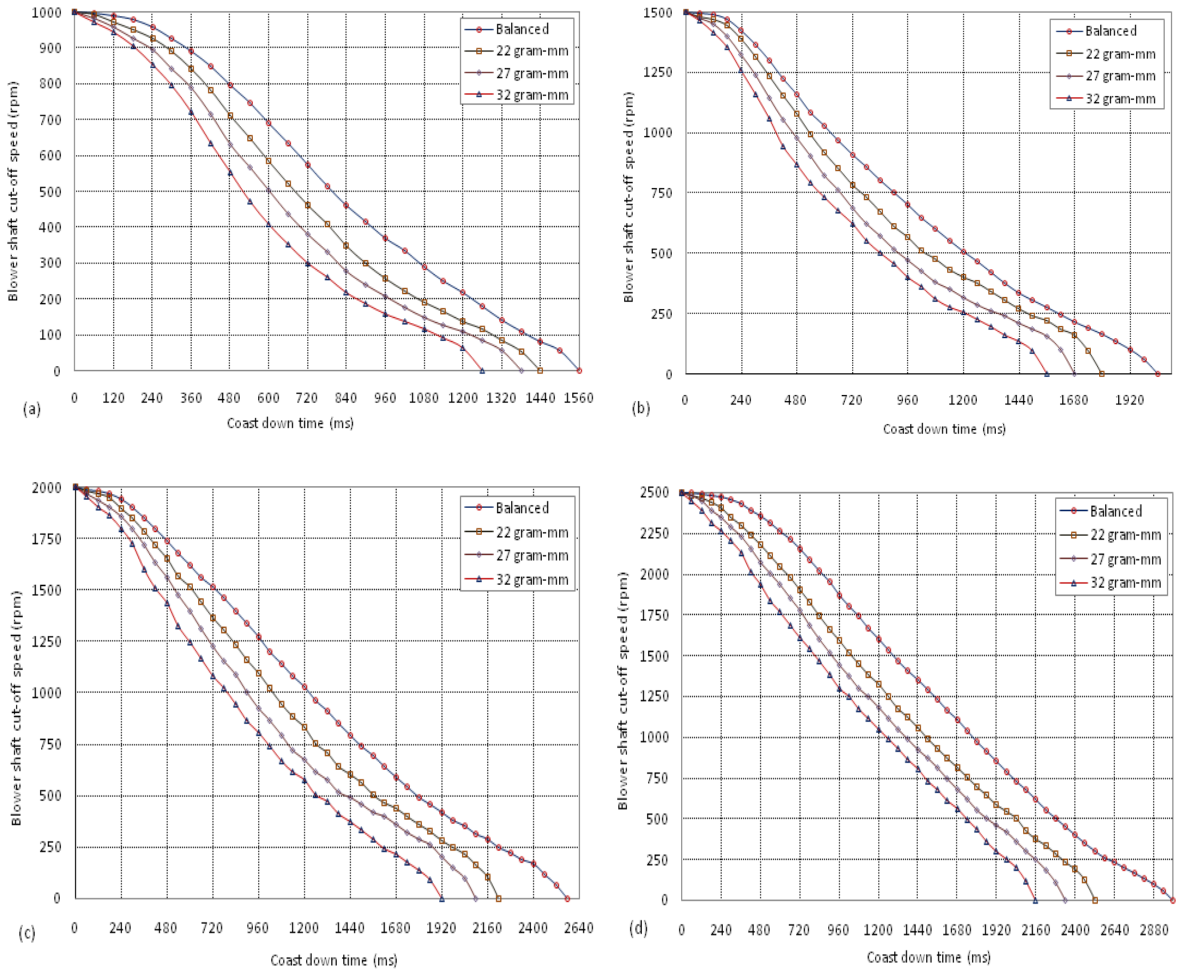

Fig2. *Coast Down Time profile curves for a) balanced, b) 22 gram-mm, c) 27 gram-mm and d) 32 gram-mm unbalance conditions at blower shaft cut-off speed of 1000 rpm, 1500 rpm, 2000 rpm and 2500 rpm.*

Since the CDT profile curves at healthy normal operating condition has longer CDTs compared to faulty condition at different cut-off speeds, it exhibits smooth transition between fluid friction zone and boundary lubrication zone with a smooth and sharper curve in the transition zone. All these CDT profile curves exhibited the generic frictional behaviour during coast down similar to the frictional characteristic of design curve described by Raimondi & Boyd [10]. Deviation between healthy CDT and faulty CDT profile curve indicates the behaviour of the rotating system during coast down period and severity of fault present.

The convex shape of the CDT profile at higher cut-off speeds just before the rotor reaches zero speed indicates the predominance of the boundary lubrication zone. It can be seen that the frictional torque and the centrifugal force play a dominant role at transition zone from fluid friction to boundary lubrication zone.

The profile curves are more convex shape at the boundary lubrication zone before reaching zero speed. This can be identified in each case at different cut-off speeds. A lower profile is observed in all the cases with increase in fault levels resulting in high vibration amplitude level. The profiles at the boundary lubrication region show a more convex shape in all unbalance cases which is a clear indication of the high centrifugal force due to high levels of unbalance. The CDT values at speed 2500 rpm is found to be higher compared to CDT values at lower speeds. As the level of faults increase lower values of CDTs were observed, which can be attributed to the effect of faults on CDTs during deceleration period.

The CDT parameter is a direct measure of the total friction in a rotating system. The results show that with increase in unbalance mass, the coast down time decreases compared to baseline CDT recorded under normal healthy operating conditions. At lower cut-off speed, for increased unbalance mass, the profile of the CDT curves are more concave than at higher cut-off speeds. At higher speeds the CDT profile curves are much sharper and smoother compared to CDT profile curves at lower speeds.

The decrease in CDTs for these fault conditions are presented as CDT reduction percentage. The obtained CDT values for various unbalance conditions with the corresponding blower shaft cut-off speeds are depicted in Figure 3 as CDT reduction percentage versus unbalance mass introduced.

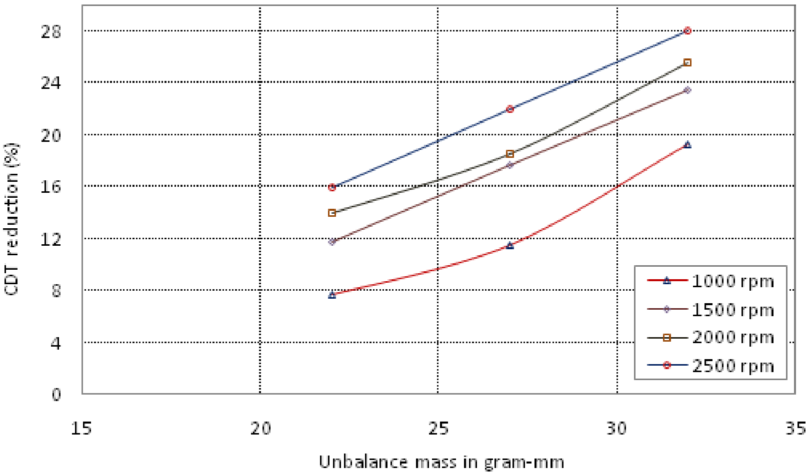

Fig3. *CDT reduction percentages at different cut-off speeds for various unbalance masses*

It is observed that the CDT reduction percentage increases with increase in unbalance mass. At lower speed and at smaller unbalance mass the impact on CDT reduction percentage is very less. At higher unbalance condition with higher speed, the impact on the CDT reduction percentage is very high, and it is noticed that there is a specific correlation between the CDT reduction percentages and the order of mechanical malfunction. The CDT reduction percentage is 28% for unbalance weight of 32 gram-mm. It is also noted that the CDT and corresponding CDT reduction percentage has an effect on cut-off speed and found to be changing in relation with the cut-off speed. And the mechanical malfunction has the considerable influence on CDT reduction percentage.

The driving torque before and after coupling were recorded under healthy conditions at cut-off speeds of 1000 rpm, 1500 rpm, 2000 rpm and 2500 rpm respectively and these torque values are compared with the corresponding measured torque values taken before and after coupling condition for different unbalance conditions. The respective torque measurements for different unbalance condition and at healthy condition are shown in Figure 4.

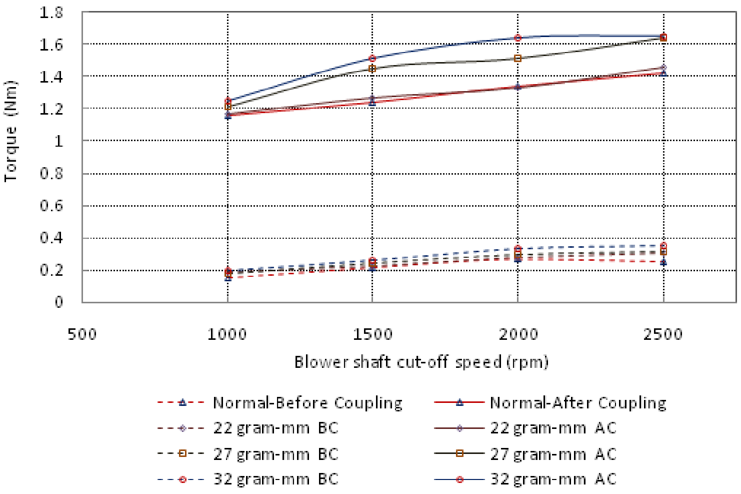

Fig4. *Torque measurements for various unbalance conditions at different blower shaft cut-off speed*

The observed torque measurements indicates that as the unbalance masses increases the torque after coupling also increases due to load on the coupling. It is observed that at higher speed, with higher order of introduced unbalance conditions the frictional torque is higher than at lower speeds.

The vibration signals were acquired for different unbalance conditions at both the blower and motor shaft bearing housing for selected cut-off speeds. The recorded time domain signals and vibration spectrums for balanced and aligned condition at blower shaft cut-off speed of 2500 rpm in all the three directions under healthy operating conditions are used as a baseline for analysing different unbalance conditions. However, only horizontal vibration data are presented for analysis and comparison since vibration amplitudes observed along horizontal direction are much higher than vertical and axial directions. Vibration spectrums at higher cut-off speed of 2500 rpm are presented to highlight the effect of unbalance fault. The vibration spectrum of frequency domain for the blower shaft cut-off speed of 2500 rpm (41.667 Hz) for balanced condition is presented in Figure 5(a). Small amount of residual imbalance and misalignment are noticed in the balanced and aligned condition, the amplitude level at 1X is 0.2122 m/sec^2, at 2X is 0.3515 m/sec^2 and at 3X is 0.1355 m/sec^2 are well within the acceptable tolerance limits.

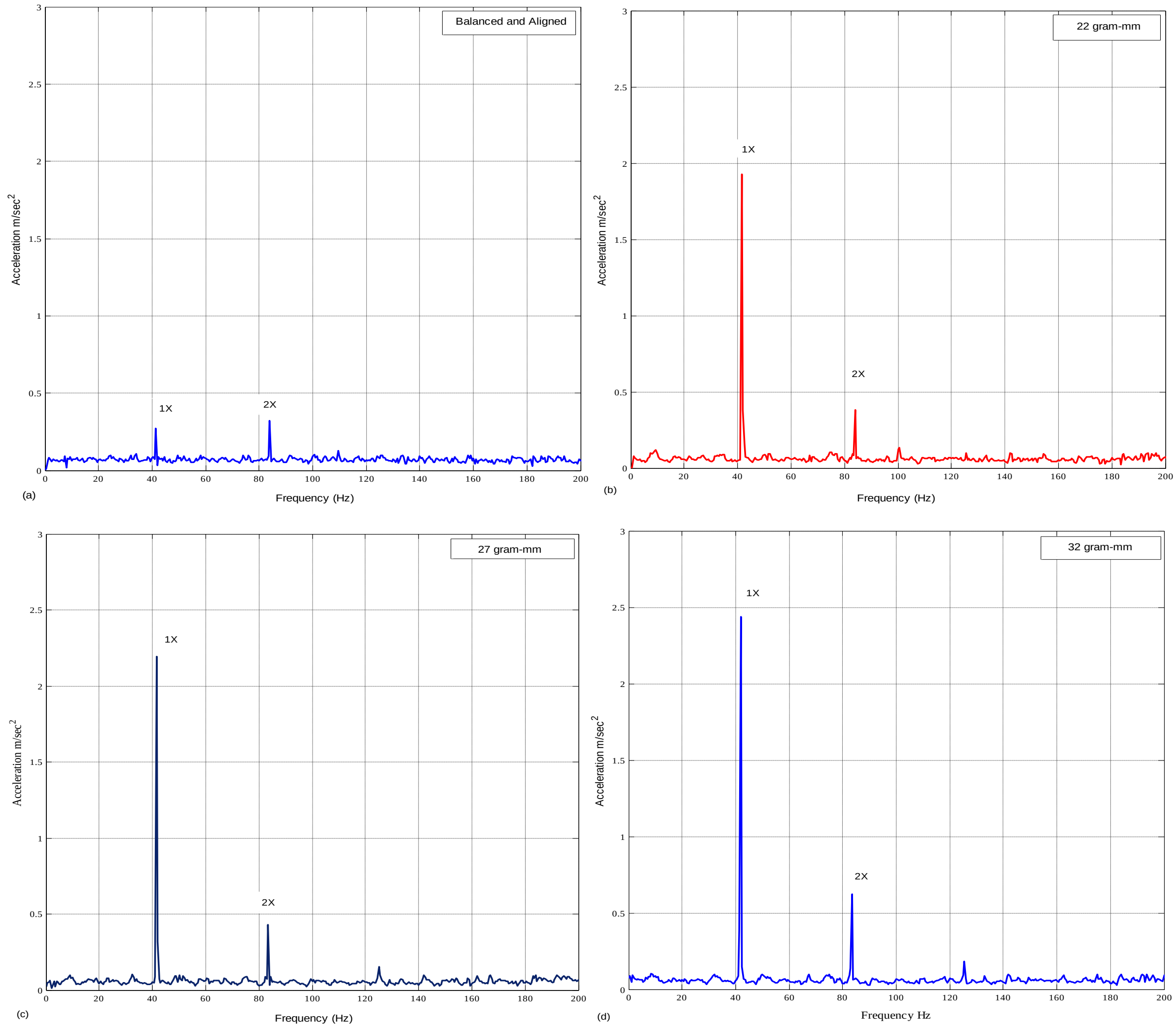

Fig5. *Vibration spectrums for a) balanced and aligned, b) 22 gram-mm, c) 27 gram-mm and d) 32 gram-mm unbalance conditions at blower shaft cut-off speed of 2500 rpm.*

In Figures 5(b-d), the vibration frequency of rotating system unbalance is synchronous, i.e., one time the shaft speed (1X), since the unbalance force rotates at the shaft running speed. For different unbalance conditions it is observed that the 1X (41.667 Hz) running speed component is the predominant frequency in the spectrum in all the cases. This clearly shows the presence of unbalance and the vibration amplitude increases as the unbalance weight increases and also vibration amplitude is a function of operating running speed. It is found that the 1X vibration amplitude components for 22 gram-mm weight is 1.928726 m/s^2 as the weight increased to 27 gram-mm and 32 gram-mm the respective 1X component increases to 2.195112 m/s^2 and 2.436275 m/s^2. And corresponding 2X vibration amplitude component for 22 gram-mm weight is 0.382751 m/s^2 as the weight increased to 27 gram-mm and 32 gram-mm the respective 2X component increases to 0.4282 m/s^2 and 0.622412 m/s^2 respectively. From this it is evident that as the unbalance weight increases, it has considerable influence on the behavior of the system and also on CDT values.

4. CONCLUSION

Condition monitoring helps in prediction and detection of any anticipated fault in machinery. Various unbalance conditions were studied and the behavior of the system during coast down period has been analysed. The CDT profile trend follows more convexity in all the cases with respect to increased unbalance condition. Frictional torque and the centrifugal force play a dominant role at transition zone from fluid friction to boundary lubrication zone at higher cut-off speeds. In this region, metal to metal contact exists between the mating surfaces, where the resistance to movement increases with decrease in rotational speed. The CDT can generally describe the mechanical behavior of the rotor system. It decreases as unbalance weight increases, and the corresponding CDT reductions percentage increases with increase in unbalance and increase in rotational speeds. There is a specific correlation between the reduction percentage in CDT and the level of unbalance with rotational speed, and hence CDT can give a measure of unbalance. As unbalance weight increases the 1X vibration amplitude component gradually increases with increase in shaft rotational speed. The unbalance has an effect on the CDT, and this is comparable with 1X vibration amplitude component. Therefore it proves that CDT could be used as a diagnostic parameter in condition monitoring of industrial rotating machinery.

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