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Coast Down Time Analysis to Analyze the Effect of Misalignment in Rotating Machinery

G.R. Rameshkumar, B.V.A. Rao, K.P. Ramachandran

Abstract*: Shaft misalignment in rotating machinery is one of the major industrial concerns. 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 rest. The exact time period between the power cut-off time and the time at which the rotor stops is called Coast Down Time. In this paper an experimental study was conducted to investigate the effect of angular misalignment in forward curved centrifugal blower test setup. Tests were conducted for various level of angular misalignment at different shaft cut-off speeds. The results show that the coast down time decreases with increase in level of angular misalignment. At higher speed and at higher level of angular misalignment, the impact on percentage reduction in CDT is very high and there is a specific correlation between the percentage reduction, cut-off speeds and the level of introduced angular misalignment. The vibration signatures acquired at different cut-off speeds and at the various level of angular misalignment conditions. The 2X and 3X vibration amplitude components are predominant frequencies and increase as the angular misalignment 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.

***Index Terms*—Angular Misalignment, Coast Down Time, Condition Monitoring, Forward Curved Centrifugal Blower.**

I. INTRODUCTION

Increased machine availability, reduction in unscheduled down time and minimum maintenance cost can be achieved by adapting condition monitoring. Shaft misalignment is one of the major concerns in rotating machinery. Misaligned shaft causes premature wear or even catastrophic failure of components in the machinery. Shaft misalignment occurs when the centerlines of rotation of two are more machinery shafts are not in line with each other. Two types of misalignments: parallel misalignment when the shaft centerlines of the two machines are parallel, but offset to each other and angular misalignment, when the shaft centerlines are not parallel, but inclined to each other [1] occurs in rotating machinery. It is practically very difficult to achieve perfect alignment of the driving and driven shafts. Vibration signatures are widely used as a useful tool for studying progressing machine malfunctions, and also form the baseline signature for further comparative monitoring to detect mechanical faults [2].

II. Coast Down Phenomenon (CDP) and Coast Down Time (CDT)

In this work Coast Down Time (CDT) is used as a diagnostic parameter to detect and analyze the effect of shaft misalignment in rotating machinery in service at early 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 rest. The behaviour of the 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 [3]. The CDP is inherent of a system and the CDT depends on inertia forces of the system components, tribological behaviour and environmental effects such as fluid drag. Ramachandran et al. [4] conducted experiments to approach the misalignment using vibration, orbit and CDT phenomenon and they found that improper alignment leads to extensive vibration and noise and the increase in misalignment reduces the CDT. Santhanakrishnan et al. [5] used CDP to investigate experimentally the influence of misalignment on CDT in the case of flexible rotors in hydrodynamic journal bearings and found that the deceleration speed versus CDT resembles the Stribeck friction curve [6]. Sekhar and Prabhu [7] established in their work that there will be severe vibrations in rotating machines with improper alignment of shafts and proposed a theoretical model of a rotor-bearing system using higher order finite element method (FEM) analysis. Arumugam et al. [8] evaluated experimentally the performance characteristics of a misaligned three-lob journal bearing by considering CDT, vibration response, minimum film thickness, stiffness and damping coefficients of the fluid film, system natural frequency and damping factor as monitoring parameters. Al-Hussain and Redmond [9] studied the effect of angular misalignment on the stability of rotating machinery by considering two rotors connected by flexible coupling mounted on two hydrodynamic bearings. The hydrodynamic bearings were modeled using standard eight coefficient model. Saavedra and Ramirez [10-11] developed a theoretical model to

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determine the dynamic behaviour of misaligned shaft rotors connected by a flexible coupling and verified experimentally. Attia Hilli et al. [12] developed a theoretical model describing load, vibration and failure mechanism for shaft misalignment. Vibration response as well as the reaction in bearings can be obtained using this method and analyzed. Estupiflan et al. [13] analyzed the energy losses due to misalignment in rotating machinery by establishing a correlation between vibration levels, energy consumptions and different degrees of misalignment. Extensive studies were made by researchers [14-15] using vibration analysis for studying misalignment, pointing complexity of diagnosis for misalignment with vibration analysis. In particular, the literature on the CDT analysis for considering the effect of misalignment in rotating machinery is hardly found and is 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.

All the above referred investigators conducted extensive experimental investigation on De Laval (Jeffcott) rotor system supported between two bearings. However, an industrial environment to assess the CDT as a condition monitoring parameter is not found. Centrifugal Blowers are one of the examples of rotating machineries, and are widely used for industrial applications due to their compactness and performance. In this paper an attempt is made to investigate the use of CDT analysis as one of the condition monitoring parameter on a forward curved centrifugal blower to assess the effect of angular misalignment and for understanding the mechanical behaviour of system. Further, CDT analysis is compared with vibration signature analysis for identifying the level of misalignment.

III. EXPERIMENTAL TEST SETUP

The Fig. 1 shows the photographic view of Forward Curved Centrifugal Blower experimental test setup [16] which is used for this investigation. A forward curved (FC) centrifugal blower is mounted on shaft diameter of 20 mm at the center position between two anti-friction bearings. The shaft is simply supported between two Z type SKF antifriction ball bearings. An electromagnetic coupling is used to connect blower shaft to a variable speed DC motor shaft. Motor side shaft is supported by one each Z type and P Block self-aligning bearing. Two inductive proximity sensors are used to measure the speeds of blower and motor. The whole test setup 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. The specifications of forward curved centrifugal blower used for this investigation are given in Appendix A.

An instrumentation control panel is built to display and control the variables. Two inductive proximity sensors are used to measure the speeds of blower and motor 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, blower speeds and coast down time for each test run for selected speeds. 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 CDTs with an accuracy of 0.06 seconds intervals and corresponding deceleration speed of blower and motor.

LabVIEW7® application software developed for FFT analyzer is used to acquire vibration signals data via 4 channel sensor input module Data Acquisition Device. Three piezoelectric accelerometers (Model 600A12, 18 kHz) were used to acquire vibrations signals in vertical, horizontal and axial directions. Angular misalignments between blower shaft and motor shaft were introduced in the experimental setup by adjusting the gap between the steel plate and main support frame in one direction. Shims of specific thickness were inserted between the gaps towards right side of the blower shaft at two parallel sides of the steel plate by adjusting the screws in one direction as shown in Fig. 2. The corresponding inclined angular misaligned angles were calculated.

IV. EXPERIMENTAL PROCEDURE

In order to minimize the external effect of external disturbances due to the fluctuation in power source voltage, frequency etc that can have appreciable effect on CDT, an electromagnetic coupling is used to ensure that the entire centrifugal blower system is completely free from the power source during coast down test run. The blower shaft and motor shaft are carefully aligned and balanced in both vertical and horizontal directions using reverse dial indicator method, and this aligned and balanced system is used as a reference for

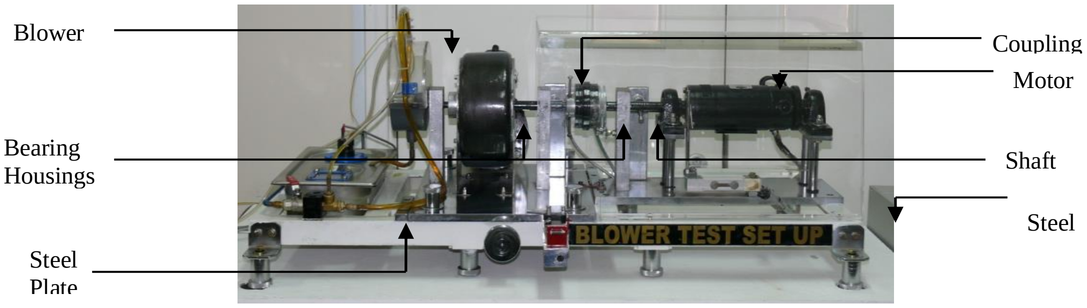

Figure 1: Forward Curved Centrifugal Blower Experimental Test Setup

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creating the required level of angular misalignment conditions.

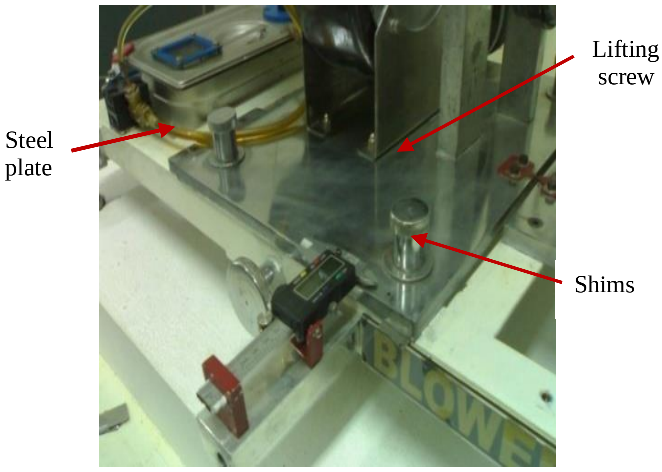

Figure 2: Steel plate and shims used for creating angular misalignment

The main objective of this study is to emphasize the use of CDT analysis to detect and analyze the effect of angular misalignment on centrifugal blower rotating machinery. Various levels of angular misalignment conditions were created between blower and motor shaft to understand the mechanical behavior of the system. The baseline coast down time for each test run and vibration signatures spectrum along vertical, horizontal and axial directions at blower end shaft bearing housing under normal operating conditions are recorded during the test run. The experimental tests at different blower shaft cut-off speeds i.e., 1000, 1500, 2000 and 2500 rpm respectively have been carried out to record coast down time. Three level of angular misalignment 0.031^0, 0.0535^0, and 0.084^0, respectively have been introduced between blower and motor shafts at blower shaft end for each test to study the angular misalignment effect. Vibration data was acquired at both blower and motor end shaft bearing support housings in vertical, horizontal and axial directions. The sampling frequency used for data acquisition was 16 kHz.

V. RESULTS AND DISCUSSIONS

The profile of the CDT curves, the speed in rpm versus CDT in milliseconds for aligned condition and intentionally introduced 0.031^0, 0.0535^0 and 0.084^0 of angular misalignment between the blower shaft and motor shaft for cut-off speeds of 1000, 1500, 2000 and 2500 rpm respectively are shown in Figs. 3-6.

The typical CDT curve is characterized by three zones, at the beginning of the coast down a small convex shape, at the middle of the coast down as concave and at the end of the coast down a small convex shape. The shape of the CDT profile curve resembles the Stribeck frictional curve and follows the pattern characterized by the Raimondi-Boyd curve. 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 CDTs obtained. It is observed that higher energy dissipation takes place during middle of the coast down. It was found that as angular misalignment increases, the CDT decreases, which is due to the increased power loss and increased torque in the bearings.

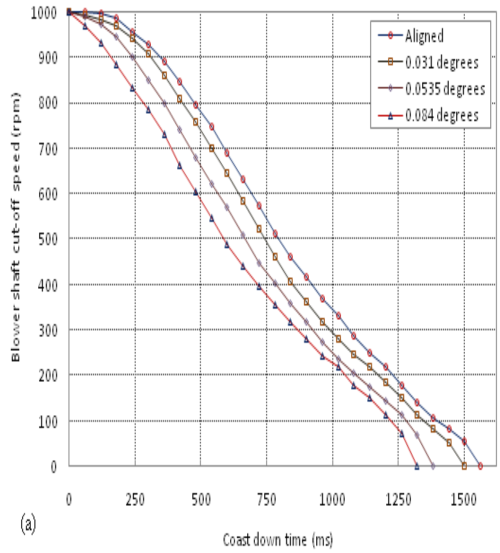

Figure 3: Coast Down Time profile curves for various levels of angular misalignment at blower shaft cut-off speeds of 1000 rpm

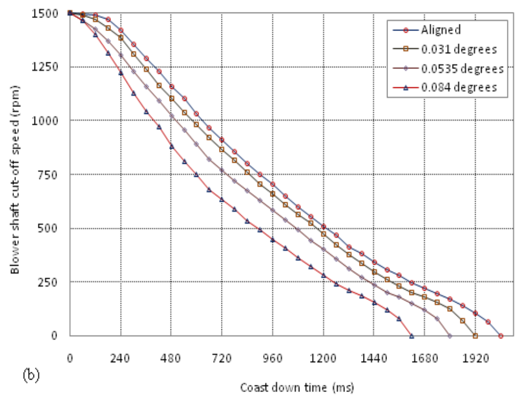

Figure 4: Coast Down Time profile curves for various levels of angular misalignment at blower shaft cut-off speeds of 1500 rpm

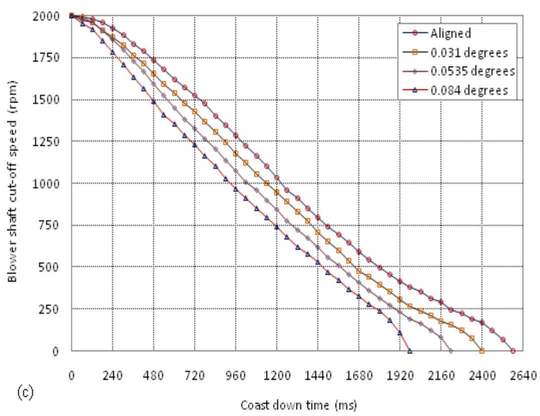

Figure 5: Coast Down Time profile curves for various levels of angular misalignment at blower shaft cut-off speeds of 2000 rpm

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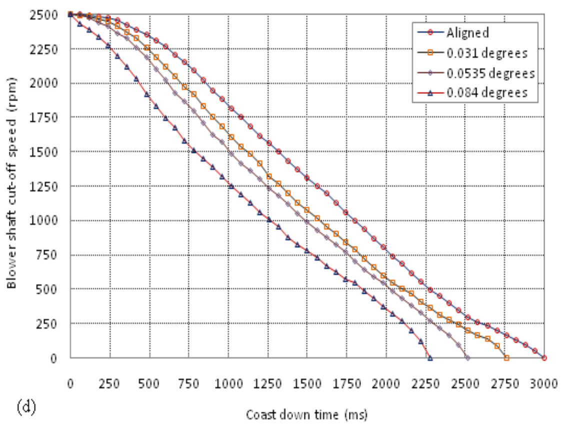

Figure 6: Coast Down Time profile curves for various levels of angular misalignment at blower shaft cut-off speeds of 2500 rpm

The CDT reduction percentage [17] was calculated using relation given below for all obtained CDT values for various levels of angular misalignments with the corresponding blower shaft cut-off speeds.

CDT reduction percentage=
[(baseline CDT- obtained CDT)/baseline CDT]*100

The CDT reduction percentage for various angular misalignments at different blower shaft cut-off speeds are shown in Fig. 7. It is noticed that the reduction percentage in CDT increases as angular misalignment increases. At higher levels of misalignment with higher speed, the reduction percentage is high, and from this it is found that there is a specific correlation between the percentage reduction in CDT and the level of angular misalignment. It is also noted that the CDT and corresponding reduction percentage in CDT has an effect on cut-off speed and found to be changing in relation with the cut-off speeds.

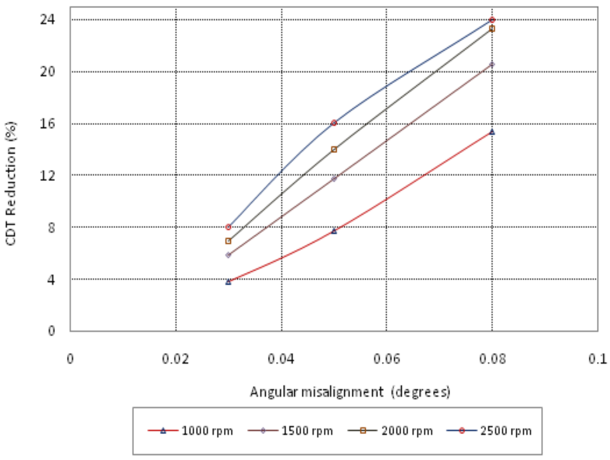

Figure 7: CDT reduction percentage at different blower shaft cut-off speeds for various angular misalignments

CDT profiling is done by estimating the Coast Down Factor [18] due to the complexity in exactly identifying the particular fault i.e., shaft angular misalignment by solely examining the CDT profile curves at boundary lubrication region alone.

CDF for various levels of angular misalignment conditions at different blower shaft cut-off speeds were calculated and plotted against CDT and are shown in Figs. 8-11 respectively.

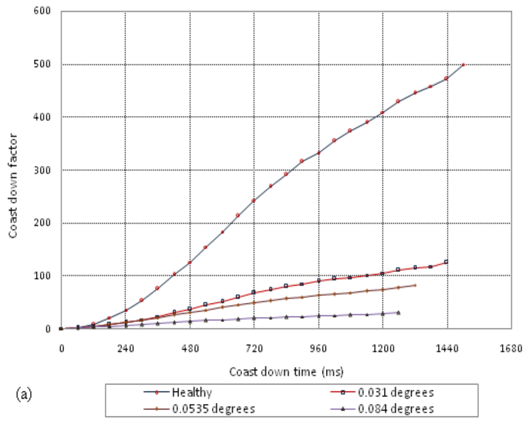

Figure 8: Coast Down Factor trend at blower shaft cut-off speeds 1000 rpm for various angular misalignments conditions

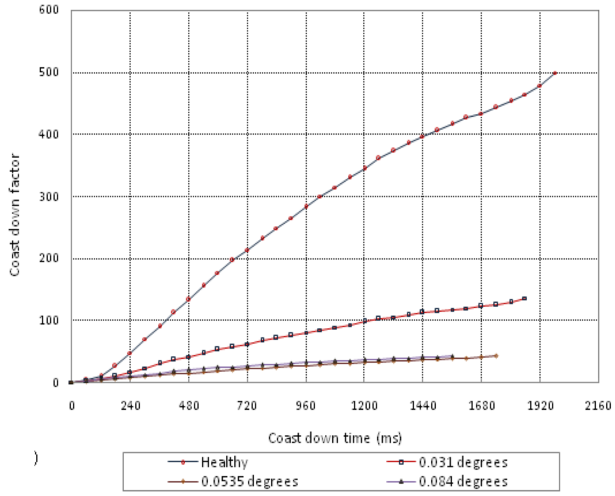

Figure 9: Coast Down Factor trend at blower shaft cut-off speeds 1500 rpm for various angular misalignments conditions

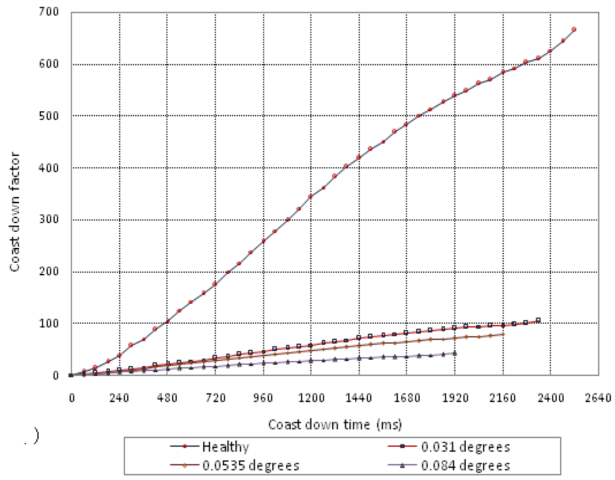

Figure 10: Coast Down Factor trend at blower shaft cut-off speeds 2000 rpm for various angular misalignments conditions

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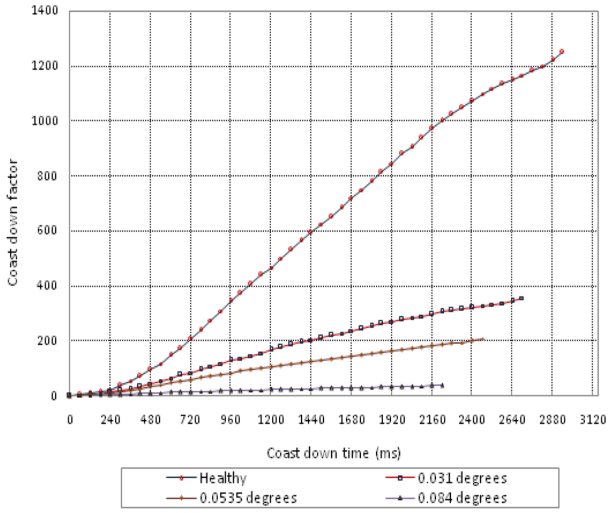

Figure 11: Coast Down Factor trend at blower shaft cut-off speeds 2500 rpm for various angular misalignments conditions

In the CDF trend curves, it is observed that higher CDF values represent the mixed film lubrication or boundary lubrication and lower CDF values represent the hydrodynamic lubrication region. From these trend curves, it can be noted that, at higher speed with increased angular misalignment, the trend curve is more curvilinear in nature in the boundary lubrication region.

The vibration spectrums at higher cut-off speed are selected for discussion for various angular misalignments. The vibration spectrum of frequency domain for the blower shaft cut-off speed of 2500 rpm for aligned condition is presented in Fig. 12. Small amount of residual imbalance and misalignment are noticed in the 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.

The vibration spectrum for the blower shaft cut-off speed of 2500 rpm for 0.031^0 angular misalignment is presented in Fig. 13, for 0.0535^0 of angular misalignment is shown in Fig. 14, and for 0.084^0 of angular misalignment is presented in Fig. 15.

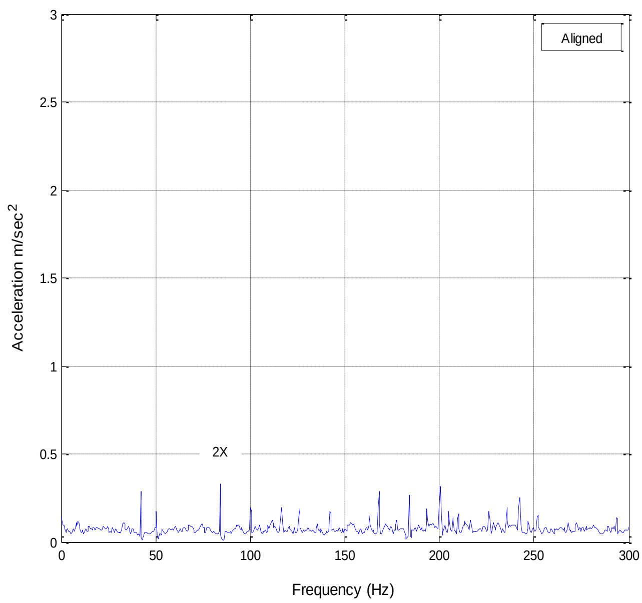

Figure 12: Vibration spectrum for aligned condition at blower shaft cut-off speed of 2500 rpm

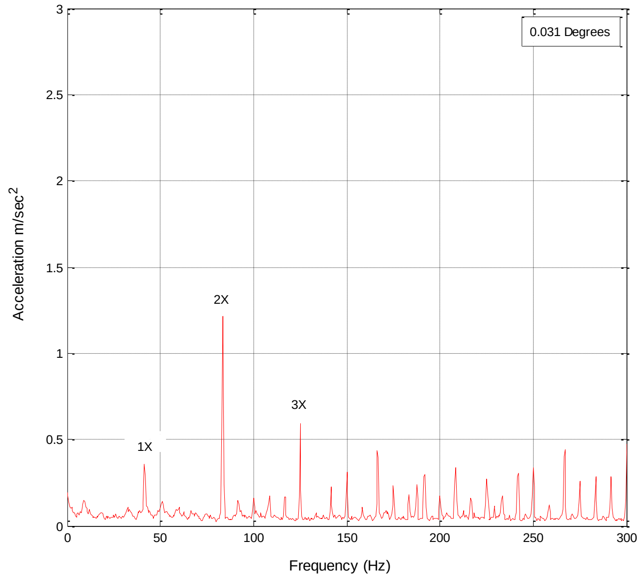

Figure 13: Vibration spectrum for 0.032 degree angular misalignment at blower shaft cut-off speed of 2500 rpm

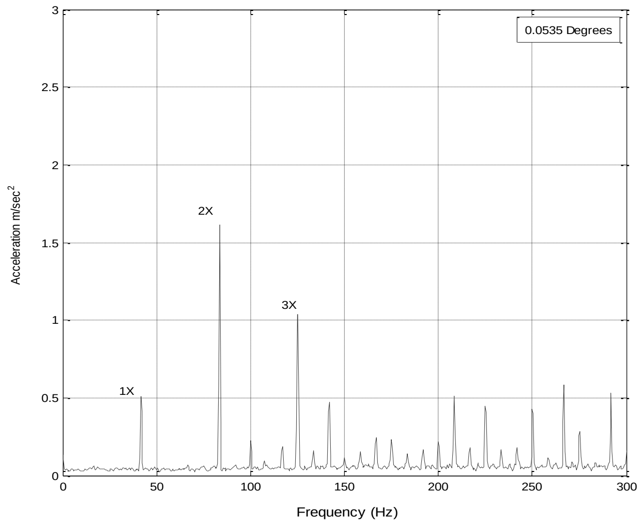

Figure 14: Vibration spectrum for 0.0535 degree angular misalignment at blower shaft cut-off speed of 2500 rpm

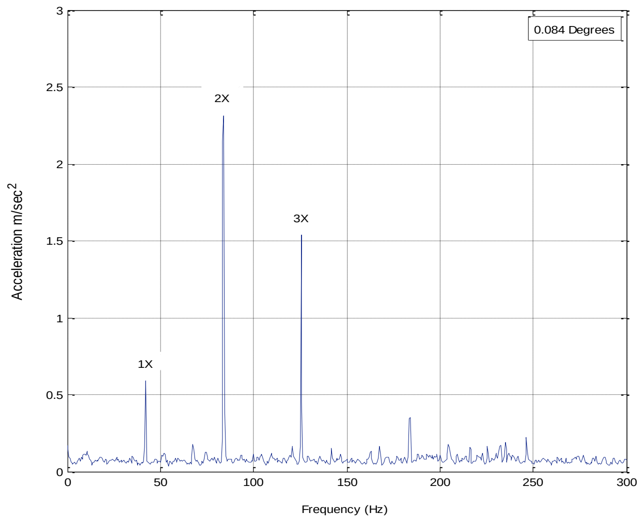

Figure 15: Vibration spectrum for 0.084 degree angular misalignment at blower shaft cut-off speed of 2500 rpm

It is observed that the 2X

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running speed vibration amplitude component is the predominant frequency in the spectrum in all the three cases. A slight increase also is noticed in 3X running speed vibration amplitude component with increase in angular misalignment. This clearly indicates the presence of angular misalignment and the amplitude increases as the level of angular misalignment increases and also vibration amplitude is a function of operating running speed. Increase in 1X amplitude level is also observed, which is because of centrifugal force effect due to residual unbalance. Also, due to misalignment, more strain is induced on the coupling, which causes increased values of vibration amplitude at 2X and 3X shaft running speed. For increased angular misalignment, vibration at multiple harmonics are evidence due to mechanical behavior of the system, and also due to the strain induced in the shaft and because of interaction between the impeller blades and the air drag force.

VI. Industrial Case Study

To validate the experimental results an industrial case study was carried out at water pumping station which use centrifugal pump. CDT was used as a monitoring tool and the results were analyzed comparing with experimental results to validate the efficiency of CDT as a diagnostic parameter in condition monitoring of industrial rotating machinery. The study was carried out in a centrifugal pump and motor assembly. The centrifugal pump is connected through flange coupling (Fenner HRC 280) to motor (BR 12C), both aligned in horizontal direction. The pump was in continuous operation from the day of installation unless there is a maintenance work. Due to the fixed configuration of the pump and motor assembly, pump was monitored by recording CDTs in seconds using a precision stopwatch once a week continuously for 20 weeks to assess the centrifugal pump behaviour under the full load operating conditions with a constant rotational speed. Since this was the first time CDT as a monitoring tool is implemented in a water pumping station, there was no past CDT data available for healthy operating conditions for considering as a base line CDT. The recorded CDT data at cut-off speed of 1480 rpm for 20 weeks are expressed in a graphical format as CDT versus number of weeks is shown in Fig. 16.

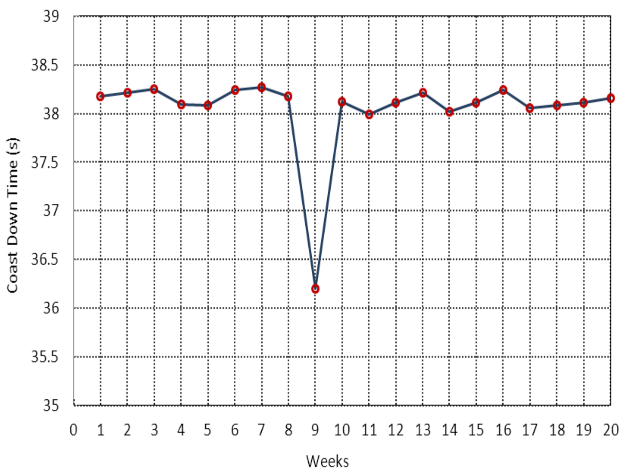

Figure 16: Coast Down Time data for 20 weeks

It can be seen from the CDT plot that the recorded CDT values are almost constant up to the 8th week. However, in 9th week, there is a decrease in CDT value compared to the values recorded for previous eight weeks, which is an indication of the possible mechanical fault developed in the system. The CDT reduction percentage is 5.20%. This is in agreement with the earlier finding that CDT decreases with increase in mechanical faults. It was not possible to attribute the decrease in CDT to exact nature of faults as there was limitation in using the instrumentation for CDT measurement. However, if an application software is used along with instrumentation for acquiring sufficient data of CDT at specified cut-off speed, and time intervals until the pump reached to a halt along with deceleration speed, accurate CDT profiles can be plotted. It can be deduced whether the fault is due to rotor unbalance or shaft misalignment based on the CDT profile plots. At this stage, in order to confirm the findings, it was decided to check the alignment and balance conditions. First, alignment was checked using dial gauge indicator method, it was found that a slight deviation between the motor shaft and pump shaft was noticed. A corrective action was taken by performing an alignment process between the pump and motor shaft assembly. The machine assembly was reactivated after alignment. The CDTs were recorded, it was found that the CDT values were within the range of CDTs observed during previous 8 weeks. From 10th week onwards CDTs were recorded upto 20th week. It was observed that the steady values in CDTs during these period.

VII. Conclusion

In the present experimental investigation the effect of angular misalignment was studied for different levels of angular misalignment introduced. The baseline CDTs were recorded for different running speeds under normal operating conditions, and are then used as reference for analysis. The CDT decreases as angular misalignment increases, the percentage reductions in CDT, which increases with increase in angular misalignment and rotational cut-off speeds. There is a specific correlation between the reduction percentage in CDT and the level of angular misalignment with rotational speed. This experimental investigation technique provides a simple method of evaluating the effect of angular misalignment on forward curved centrifugal blower using coast down time analysis and shown great potential to use this technique to predict mechanical malfunction. In comparison with vibration analysis, the 2X and 3X vibration amplitude components are gradually increases with increase in angular misalignment and shaft rotational speed. During the course of time, by frequent monitoring of the rotating system and recording the CDT values for selected operating speeds and the corresponding percent reductions in CDT is done. If any variations in the baseline CDT and the obtained CDT values and the corresponding increase in CDT reduction percentage, one can detect, predict and assess the severity of angular misalignment.

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The traditional vibration analysis is performed along with CDT analysis to identify the angular misalignment, find the root cause and further corrective action can be initiated to avoid serious damage and machinery failure. The industrial case study presented demonstrates how a CDT can be used as a monitoring tool to detect the shaft misalignment

fault. This gives supports to the earlier findings that the shaft misalignment fault have an effect on CDTs i.e., CDT value decreases with increase in mechanical faults. Therefore it proves that CDT could be used as a diagnostic parameter in condition monitoring of industrial rotating machinery.

APPENDIX - A

Specifications of Forward Curved Centrifugal Blower

Symbol	Descriptions	Specifications
d_2	outer diameter	135 mm
d_1	inner diameter	110 mm
n	number of blades	36
l	chord length	25 mm
b	blade width	71 mm
t	blade thickness	1.3 mm
β_1	blade inlet angle	112^0
β_2	blade outlet angle	129^0
w	blade channel width	10.20 mm
d_1/d_2	diameter ratio	0.815
A	blower end exit duct area	0.00295 m^2
W	weight of blower	2 kg

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