FALIURE MODE EFFECT ANALYSIS OF FLEXIBLE MECHANICAL COUPLINGS USING DAS SYSTEM FOR TORQUE AND VIBRATION MEASUREMENT ON A ROTOR-SHAFT ASSEMBLY

Abstract

Flexible mechanical couplings are widely used in rotor shaft assembly. Understanding their failure characteristics is therefore important. Through various sets of experiments using torque and vibration measurements this paper finds the root causes of the failure of flexible couplings. The study proposes a simple dynamic online condition monitoring of the rotating system to effectively understand the cause of failure of mechanical couplings and its effect. The research also affirms that the misalignment response is directional. The harmonic response of misaligned rotor vibrations is affected by the type of coupling. The experiments are conducted on two commercially available flexible couplings. The research describes the use of an online DAS system to analysis the failure data of the couplings. The data obtained from the DAS system is further used to list the various preventive methods for any mechanical assembly. The DAS was assembled with the mechanical assembly. The vibration profiles and torque variations acquired from measurements are recorded for various types of misalignment. Based on the results, the developed measurement system is checked for robustness, dependability and accuracy.

Keywords: Vibration Response, Torque Measurement, Data Acquisition System(DAS), Fish Bone Diagram

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I. INTRODUCTION

Couplings connects the load to the driver, and if they fail, the rotating element will not function properly. Couplings can fail for a variety of reasons, the most common of which is misalignment. If the coupling is not perfectly aligned, it can cause excessive wear on the parts and eventually failure. Poor installation, incorrect size, and material issues are also causes of coupling failure. Mechanical coupling failure can have a significant impact on the operation of a facility. A faulty coupling can cause the system to shut down completely, resulting in a loss of output. This may result in increased maintenance costs and the need for replacement parts. Furthermore, coupling failures can be hazardous due to catastrophic failure.

The current study is an attempt to investigate the interaction of various types of misalignment that may coexist in a running rotor. The study demonstrated that different types of misalignment can be distinguished using simple measurements. Similarly, industrial machinery condition monitoring maintenance programs can be easily implemented without the need for specialized equipment or sophisticated signal processing techniques. Based on the increase in torque and power loss, it is likely to use indirect emergency recognition techniques for shaft misalignment detection. A few extra load torques on a shaft are caused by shaft misalignment(M. J. Hota and Dhiman 2021)[1].

The accuracy and reliability of systems are becoming increasingly important with the widespread use of servo-mechanism in systems and controls. Unwanted vibrations in the motor-shaft assembly can cause problems with automated systems. Proper assembly and detection of gradual misalignments between these assemblies at the coupling end are critical. Most automated systems use flexible couplings to connect mechanical shafts to servo-motors, such as in NC/CNC machines, robotic joints, and machine tools. These industrial automations necessitate greater precision in the rotary elements. The condition monitoring of such systems must be both dependable and simple. The current study is easily applicable to complex mechanical systems with high processional controls. The DAS system can easily deduce the dynamic behavior of the system under the influence of misalignment or any other imbalance because the study presents an online dynamic measurement system.

A Data Acquisition System (DAS) is a computerized system that collects data from the real world, converts it to electrical signals, and then processes it for storage and display on a computer. The entire system is controlled and operated by a software application. These systems are widely used in the commercial and industrial sectors. They are used to collect, store, and process data.

Data acquisition systems are classified into two types:
1. Analog data acquisition system
2. Digital data acquisition system

According to Villarroel, Zurita, and Velarde (2019)[3] analog data acquisition systems generate analog output, whereas digital data acquisition systems generate digital output. When a wide frequency range is required or a lower level of accuracy is acceptable, analog DAS is used. Digital DAS is used when the physical quantity being monitored has a narrow bandwidth (i.e. when the quantity varies slowly). High accuracy and a low per-channel cost are also required. These are more advanced than analog DAS.

Digital data outperforms analog signals (I. A. Jamil, M. I. Abedin, D. K. Sarkar, and J. Islam, 2014) [5]. Among them are the following:

- Easy data acquisition
- Quick processing
- Fast transmission
- Simple display
- Less storage space required
- More accurate

Each block's function is explained below:

1. **Transducers/Sensors:** These devices convert physical quantities (such as temperature, pressure, flow, force, frequency and torque) to electrical quantities or measure electrical quantities directly. They gather data from the physical world.
   Most commonly used transducers are
   - Temperature is measured using RTDs, thermocouples, and thermistors
   - Light is measured using photo sensors
   - Force and pressure are measured using strain gauges and piezoelectric transducers.
   - Microphone to measure sound.
   - Potentiometer, LVDT, and Optical encoders to measure position and displacement

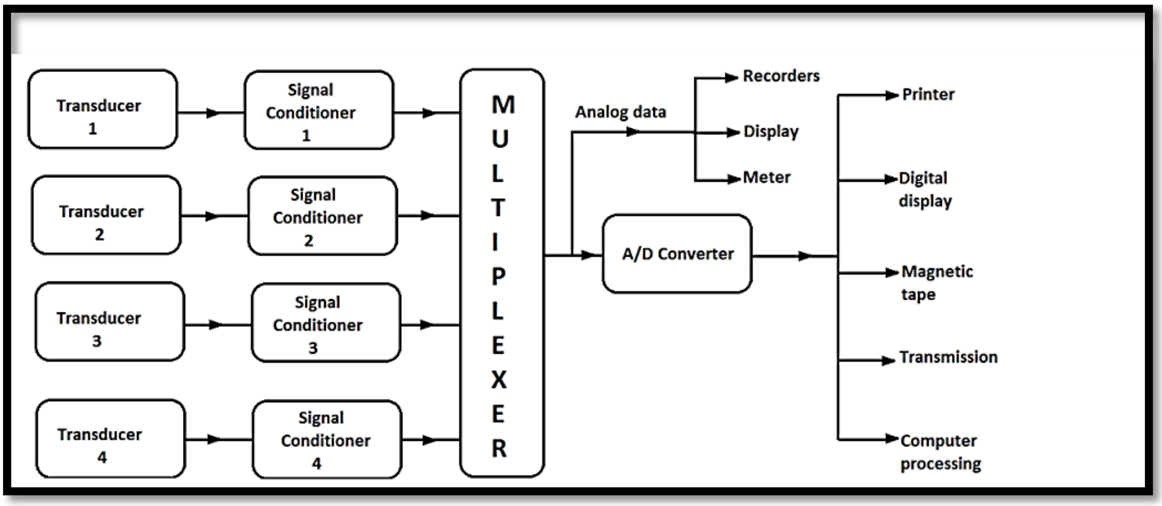


Figure 1: Block diagram of DAS system [3]

2. **Signal Conditioning Unit:** The transducer signal output may not be suitable or compatible for further processing. It could be weak, noisy, strong, or even loud. A signal conditioner amplifies and filters the signal to convert it into the suitable form.

3. **Multiplexer/Multi-Channel Data Logger:** Systems are required to monitor a large number of signals. A large number of input channels will be required if individual signal is given independent channel. Thus the cost of installation, maintenance, and replacement become prohibitively expensive. Multiplexers are used to combine multiple channels into a single channel reducing number of interface.

4. **Analog to Digital (A/D) Converters:** Computers use digital signal for processing. Therefore any analog signal must be converted to digital signals before they can be interfaced to a computer. A/D converters convert analog data into digital data.

Objectives of Data Acquisition System

Proper data acquisition is a critical activity in any signal processing system. The result of subsequent processing is determined by the acquired data quality. Therefore, selecting various elements of a DAS are critical [1]. The following points helps in choosing a system:

- Input and output required by the setup
- Characteristic of data available form sensors
- Human interface or Output Data presentation format
- Data acquisition, processing and presentation frequency
- Future upgradation requirement
- Quality and Reliability

II. INSTRUMENTATION FOR THE MECHANICAL SET-UP

1. **Mechanical Set-Up:** The proposed mechanical rig will be used to diagnose misalignment using distinct vibration features displayed in FFT. This will be a useful tool for distinguishing problems with similar frequency spectra, such as cracks and misalignments.

Machines with flexible couplings are becoming more common as a result of the dramatic advancement in machine units with automation and servo control. The lightweight steel machines have taken the place of the massive concrete supports. Steel building foundations are typically less tuned (i.e., their critical speed various natural frequencies are less than the machine's operating speed). When two or more shafts are firmly coupled together to build a continuous rotor supported by more than three bearings, this system has a statically indeterminate rotor-bearing system. Bearing reaction forces are affected by lateral misalignment. The rig could introduce a board range of angular changes and lateral alignment. The prominent features of the rig present are as discussed by(M. J. Hota and Dhiman 2021)[1].

The test rig which is being developed for the present experimentation is shown in Figure 2, the details are as given,

- The test rig set-up consists of the coupled rotor set-up with two rotors, one short length shaft directly coupled with the motor and second long shaft carrying three disks equally spaced. The second shaft is connected to the first shaft with the same coupling type as the one between motor and first shaft.
- The solid work model of the experimental set-up showing coupled rotors, a driving unit, vibration- measuring instruments and the base plate.
- The rotor-bearing assembly is mounted on sturdy base plates designed as per (Zamrodah 2016) [4]. Here in this two base plates are designed. The primary base plate is made of 100 Kg mild steel solid plate and the secondary base plate is mounted on the primary base plate.
- The dimensions and specification of the rotors are as mentioned in the Table 1.
- The Rotor 1 is connected to an electric motor via flexible coupling, however, not before ensuring perfect alignment between motor shaft and rotor shaft.
- The alignment between the motor shaft, Rotor 1 and Rotor 2 is done using the dial indicator method avoiding any initial misalignment.
- The electric motor controlled with speed controller is used to vary the speed range from 500 rpm to 3000 rpm.
- The Rotor 2 is aligned with Rotor 1 and then connected with the flexible coupling.
- The rotors are supported in the deep groove ball bearings. The bearings are housed in internally grooved housings of the bearing pedestals with retainer rings.
- The selection of bearing and coupling is done based on the range of misalignment required.

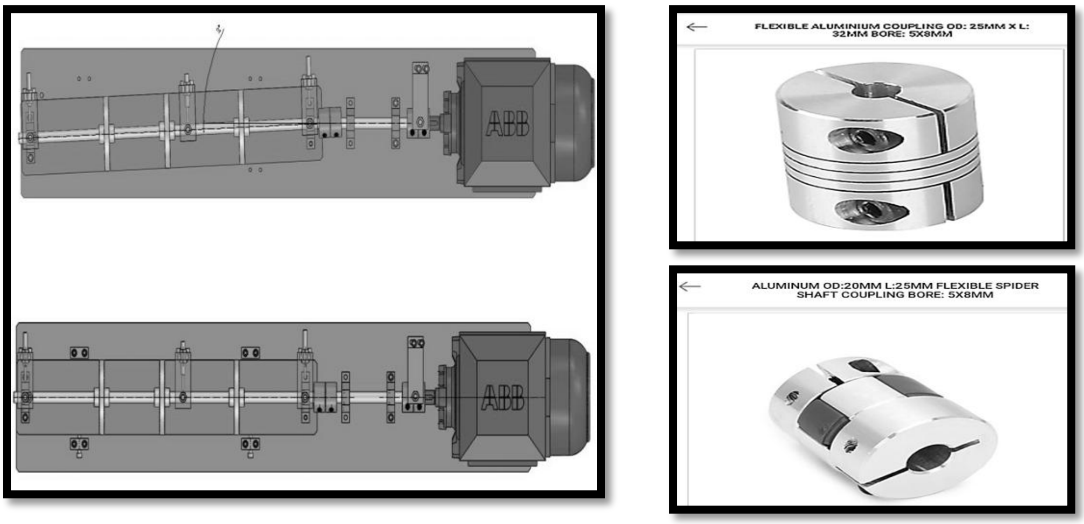


Figure 2: Solid Model of the mechanical assembly with two types of couplings used for failure analysis.

The coupling chosen for the experimental setup When deciding on the best coupling, the following factors are taken into account. Individual coupling details are chosen based on rig requirements.

- **Elastomeric Coupling**: Figure 2 depicts the elastomeric coupling. They are so-called because they have plastic or rubber material between the pair of aluminum jaws. Shock absorption can be achieved with elastomeric couplings. Another significant advantage is that there is little backlash.

- **Helical/Beam Type Coupling:** Figure 2 shows the coupling. Flexible shaft couplings, also known as beam or helical couplings, are used to transfer torque between shafts. Because of their curved beam designs, which allow for angular movement, they can handle misalignments and axial motion better than conventional rigid couplings. These flexible motor couplings can connect the driving shaft to the driven shaft while minimizing misalignment as much as possible.

TABLE 1: Rotor-Bearing-Pedestal Specifications

Shaft 1 length	135 mm	Diameter of each disc	100 mm
Shaft 2 length	600 mm	Mass of each disc	523.66 grams
Shaft major diameter	15 mm	Rotor speed	3000 rpm
No. of shafts	2	Bearing diameter	25 mm
Shaft material	4137 Alloy Steel	Bearing length	9 mm
Mass of shaft 1	360 grams	Length between the bearing pedestals	426 mm
Mass of shaft 2	689.10 grams	Coupling max diameter	32 mm
No. of discs	2	Coupling length	41m

2. **Data Acquisition system:** For further experimentation, instruments such as a Rotary torque sensor (0-100 N-m.) and a Triaxial accelerometer (0-20 G) are procured and assembled. The torque variation at the motor end is measured using a rotary torque sensor with a range of 0-100 N-m and vibration in all three directions (two radial and one axial). The installation of these sensors especially the Rotary torque sensor in place of Shaft 1 as shown in Figure 2, which is coupled to the motor with the same type of coupling under the study.

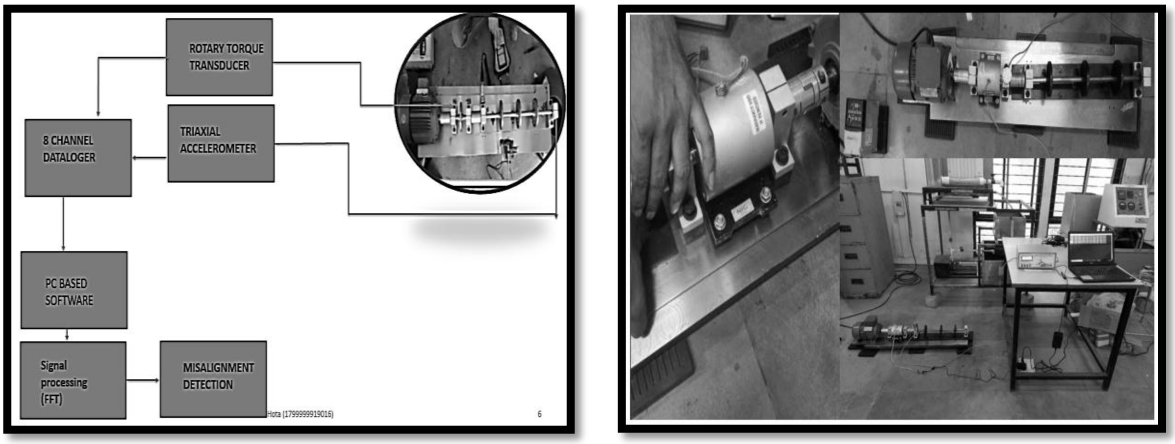


Figure 3: Complete mechanical assembly with the instrumentation(M. Hota and Dhiman 2022)[2].

III. PREPARATION FOR THE EXPERIMENTATION

(M. Hota and Dhiman 2022).[2] describe a pilot experiment using a hand-held FFT analyzer with dual channels [Vibrasound Processor: IMVA-440TM].The combination of AM and PM has been investigated by inducing varying degrees of misalignment in the vertical and horizontal planes. The study supports the conclusion that a strong 2X frequency vibration does not necessarily indicate misalignment, and it provides a well-defined diagnosis technique. The study investigates which direction (Radial or Axial) has a high frequency of misalignment due to the specific type of misalignment. The selected instrumentation is tested for sensitivity using the same experimental steps as Hota, M., and Dhiman, V.D.[2].Following the pilot testing, the setup was inspected for any permanent damage. Dial gauges were used to check the shaft for runout. The setup was also double-checked for accuracy by reassembling the motor coupling 1 with the Rotary torque sensor and coupling 2.Shaft 2 is reassembled with the coupling 2 and the torque sensor extension. The assembly is done with dial indicators to ensure that there is no more than a bare minimum of vibration. The installation is done on vibration-absorbing rubber pads. These rubber pads are mounted in such a way that there is no vibration when everything is perfectly aligned. Because rotary torque sensors are sensitive to pre-torque caused by assembly, torque sensor assembly is done as a preventive measure. There were difficulties in making the torque completely zero during the torque sensor assembly. The torque sensor is installed through the key way slots created on the sensor's extension shaft by the couplings, as shown in Figure 3.The diameter of the selected coupling is now the same as the diameter of the sensor shaft. The test rig and data logger are also connected to the triaxial accelerometer. As shown in Figure 3, the accelerometer's magnetic base is used to secure the base to the bearing housing. To control the speed, a programmable frequency drive was programmed and connected to the motor. The data logger is set up with both sensors and connected to the PC via the USB port. The data logger has eight channels, three of which are for orthogonal vibration readings, one for torque, and one for recording RPM. The couplings chosen are (i) elastomer type (ii) beam type/helical type. Before starting the rotation, the assembly completes with a torque reading of 0 Nm.

1. **Data Logging From the Transducers**: The data is logged continuously with a time step of one second. The torque variation is recorded using data logger channel no. 8.Channels 5, 6, and 7 are used to record the three axes of acceleration. The triaxial accelerometer is alternately used on each of the misaligned rotors' two bearings. Despite the fact that flexible couplings absorb a significant amount of vibration, the base is taken in a completely aligned state and further recording is performed. The Run-up and Run-down test is performed to confirm the complete alignment, and the readings are plotted for speed running up from 500 to 2800 rpm and running down from 2800 to 500 rpm at all three bearings, as shown in Figure 4.

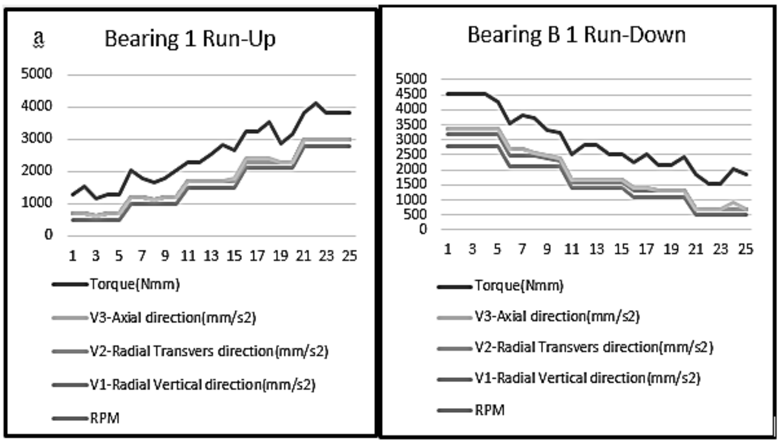


Figure 4: Run-Up and Run-Down Plots in Completely Aligned Condition on (a) Bearing 1

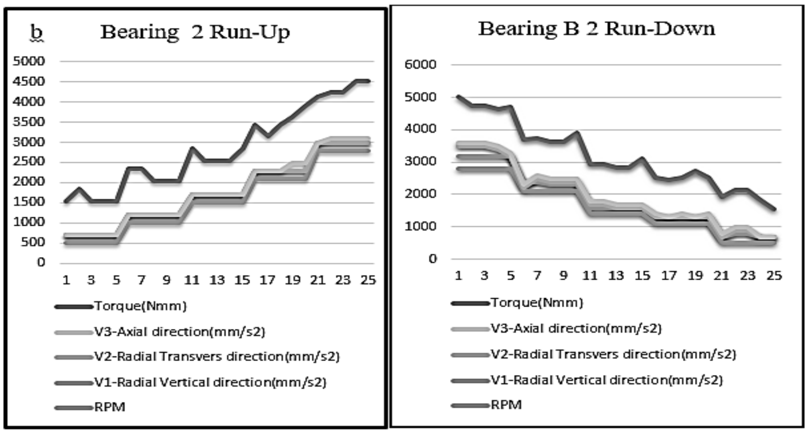


Figure 4: Run-Up and Run-Down Plots in Completely Aligned Condition on(b)Bearing 2

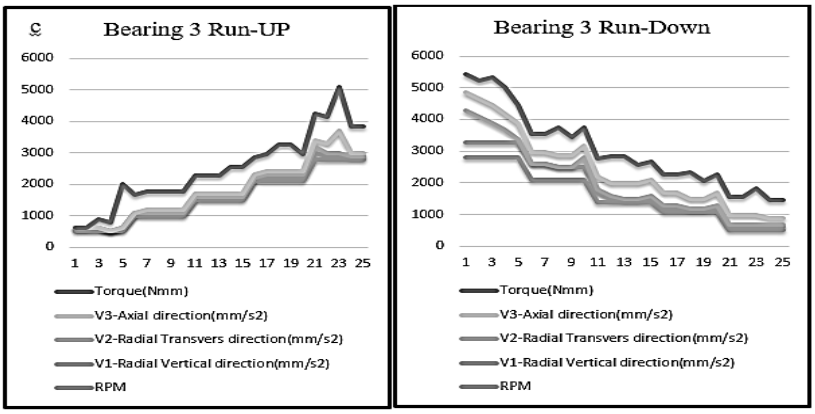
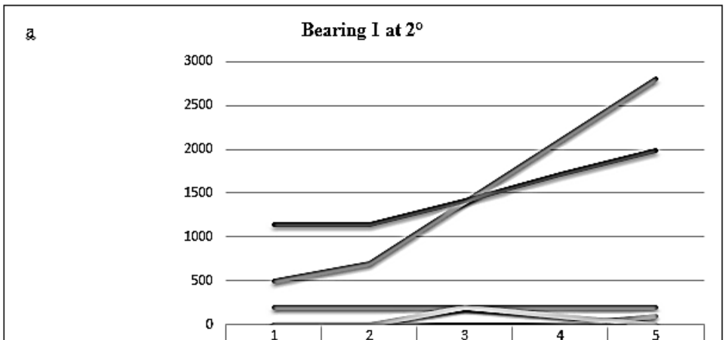


Figure 4: Run-Up and Run-Down Plots in Completely Aligned Condition on (C)Bearing 3

The plots in Figure 4 a, b, and c represent the Run-up and Run-down curves at all three bearings for a completely aligned setup. The curves almost mirror each other when running up from 500 to 2800 rpm and down from 2800 to 500 rpm. The above plots show conclusively that the test rig is stable and free of misalignment. During these recordings, there is no noise or disturbance in the system.

2. **Angular Misalignment (Am):** The secondary base plate is induced with 2^0, 3^0 and 4^0angular misalignment in the horizontal plane by shifting the secondary base plate over the primary base plate with the help of a toggle pin. The Figure 5.shows the variation of torque measured simultaneously with the three orthogonal directional measurement of the peak acceleration (RMS peak value) at various speed.



	1	2	3	4	5
RPM	500	700	1400	2100	2800
V1-radial vertical direction(mm/s2)	196.2	196.2	196.2	196.2	196.2
V2-radial transvers direction(mm/s2)	0	0	0	0	98.1
V3-Axial direction(mm/s2)	0	0	196.2	98.1	0
Torque(Nmm)	1140	1140	1420	1710	1990

Figure 5: Variations of Torque and Vibration for AM of 2°(a) Bearing 1

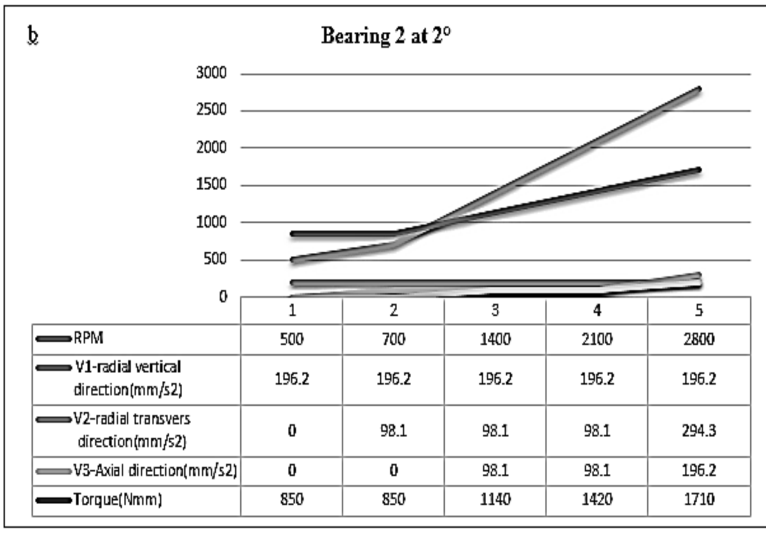


Figure 5: Variations of Torque and Vibration for AM of 2° (b)Bearing 2

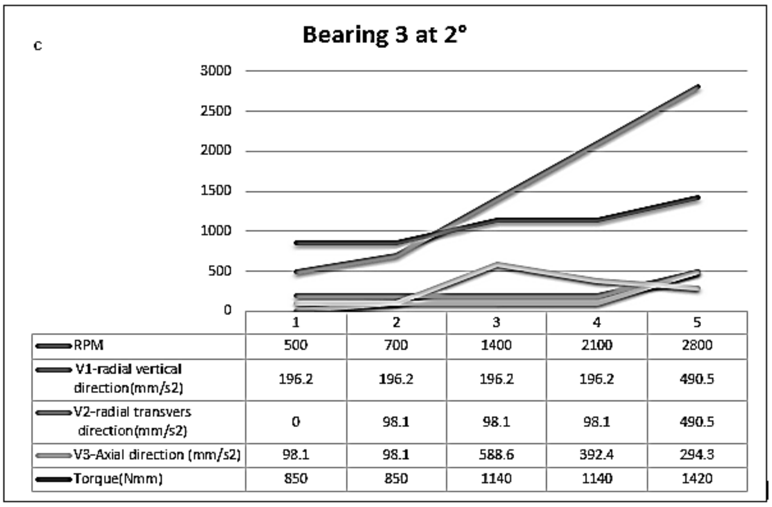


Figure 5: Variations of Torque and Vibration for AM of 2° (c)Bearing

3. **Parallel Misalignment (Pm):** The secondary base plate is to be shifted with 2mm and 3.5 mm to create parallel misalignment in the vertical plane. For inducing parallel misalignment in the perpendicular plane (i.e. Vertical Plane) the secondary base plate is lifted upward to create an offset of the shaft axis parallel upward in the vertical direction. To create this off set pre-machined sims are inserted between the secondary base plate and primary base plate. The Figure.6.shows the variation of torque measured simultaneously with the three orthogonal directional measurements of the peak acceleration (RMS peak value) at various speed for PM. It can be clearly seen and compared with the angular misalignment plots in that the axial peaks and torque drastically changed.

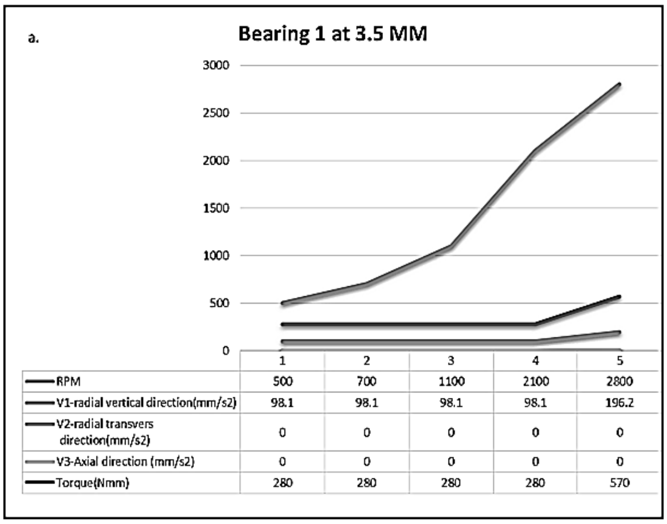


Figure 6: Variations of Torque and Vibration for PM of 3.5 mm(a) Bearing 1

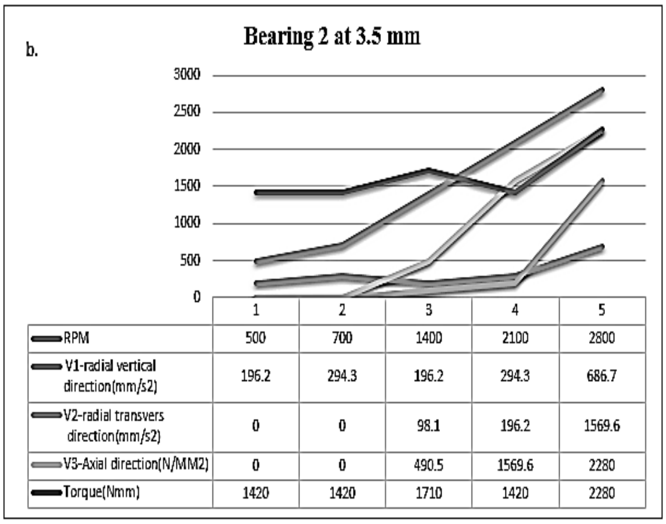
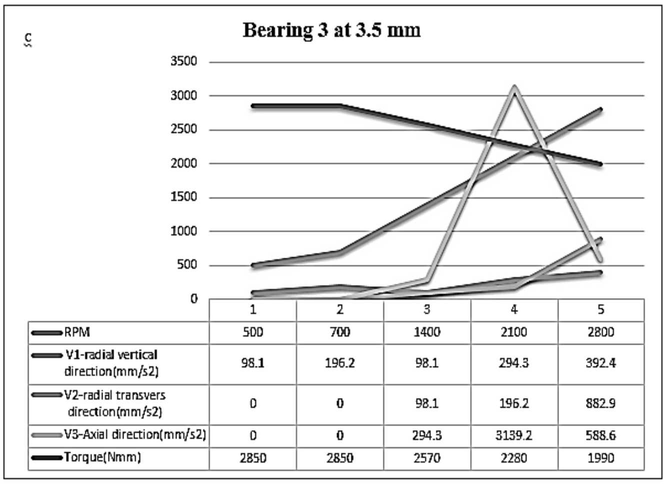


Figure 6: Variations of Torque and Vibration for PM of 3.5 mm (b)Bearing 2

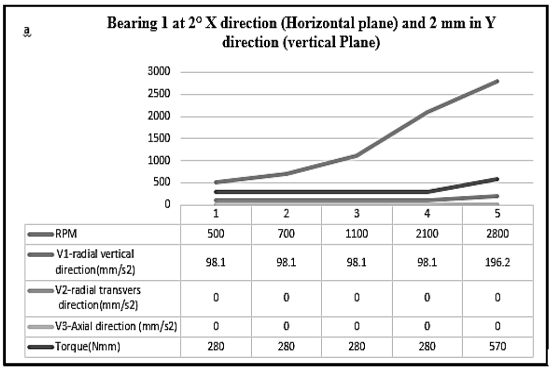


	1	2	3	4	5
RPM	500	700	1400	2100	2800
V1-radial vertical direction(mm/s2)	98.1	196.2	98.1	294.3	392.4
V2-radial transvers direction(mm/s2)	0	0	98.1	196.2	882.9
V3-Axial direction(mm/s2)	0	0	294.3	3139.2	588.6
Torque(Nmm)	2850	2850	2570	2280	1990

Figure 6: Variations of Torque and Vibration for PM
of 3.5 mm (c)Bearing 3

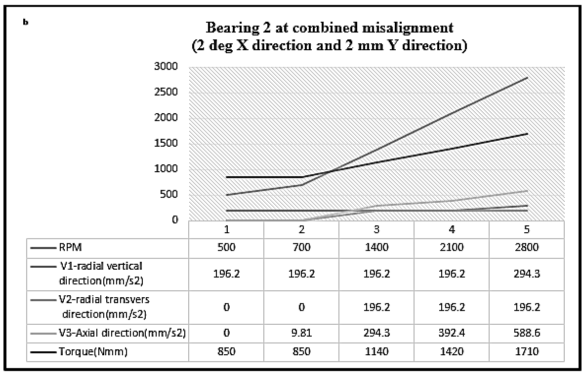
4. **Combined Misalignment (CM):** In practice, when dynamic rotating machines become misaligned for the reasons mentioned in the literature review, the condition is irreversible. They are frequently subjected to complex misalignment caused by a combination of parallel and angular misalignment. When there are parallel and angular variations in the same set of centerlines, this is the most common type of misalignment. In most cases, rigid and flexible couplings can be used to align shafts. The effect of rigid coupling is well documented in the literature; therefore, testing flexible coupling under such faults is critical. The effect of combined misalignment is investigated using a test rig that allows for this combination in perpendicular planes. By angularly shifting the secondary base plate in the horizontal direction and inserting sims beneath the secondary base plate and lifting the shaft axis in the vertical direction, the setup is now misaligned by 2° in the horizontal plane and 2 mm in the vertical plane.

The variation of torque and orthogonal RMS peak accelerations in all directions for the combined misalignment condition of 2^0 and 2 mm is shown in Figure 7.
The combined misalignment graphs show a peak in axial vibration readings and a rise in torque. The high heat generation observed in the combined misalignment condition is significant. It was discovered that the angular change in the combination had no effect on the readings.



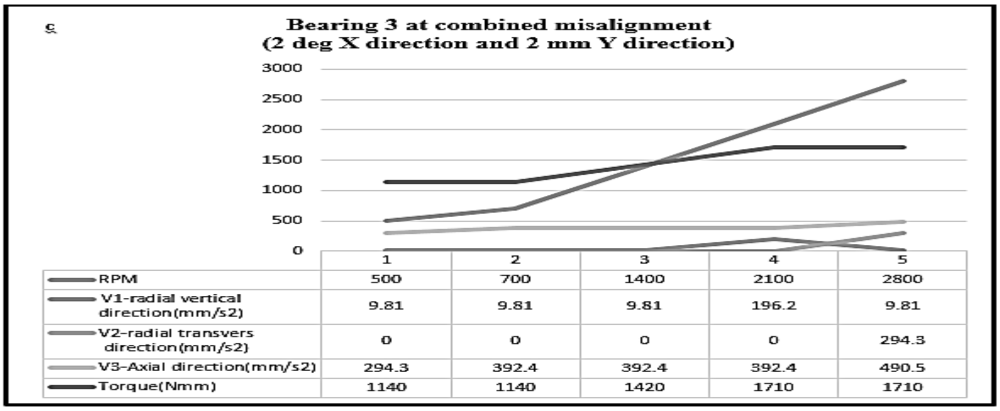
	1	2	3	4	5
RPM	500	700	1100	2100	2800
V1-radial vertical direction(mm/s2)	98.1	98.1	98.1	98.1	196.2
V2-radial transvers direction(mm/s2)	0	0	0	0	0
V3-Axial direction (mm/s2)	0	0	0	0	0
Torque(Nmm)	280	280	280	280	570

Figure 7: Variations of Torque and Vibration for CM 2° in X Direction of 2 mm in Y Direction (a) Bearing 1



	1	2	3	4	5
RPM	500	700	1400	2100	2800
V1-radial vertical direction(mm/s2)	196.2	196.2	196.2	196.2	294.3
V2-radial transvers direction(mm/s2)	0	0	196.2	196.2	196.2
V3-Axial direction(mm/s2)	0	9.81	294.3	392.4	588.6
Torque(Nmm)	850	850	1140	1420	1710

Figure 7: Variations of Torque and Vibration for CM 2° in X Direction of 2 mm in Y Direction (b)Bearing 2



	1	2	3	4	5
RPM	500	700	1400	2100	2800
V1-radial vertical direction(mm/s2)	9.81	9.81	9.81	196.2	9.81
V2-radial transvers direction(mm/s2)	0	0	0	0	294.3
V3-Axial direction(mm/s2)	294.3	392.4	392.4	392.4	490.5
Torque(Nmm)	1140	1140	1420	1710	1710

Figure 7: Variations of Torque and Vibration for CM 2° in X Direction of 2 mm in Y Direction (c)Bearing 3

IV. FISHBONE ANALYSIS OF THE FALIURE OF BOTH THE COUPLINGS

Both couplings are found sensitive to combined misalignment as the axis shifts in both the horizontal and vertical planes. The flexible element in between the coupling's jaws is responsible for the above results. Because of the design of the center element, the metal coupling could tolerate greater angular defection than the flexible coupling. While the elastomeric spider element allows the latter to take more parallel defections than the metal one.

Misalignment range tested before failure for a speed range of 500 to 2800 rpm (8.33 to 46.66Hz). Angular misalignment (AM) - 0 to 30 (horizontal plane) and Parallel misalignment (PM) - 0 to 1 mm (vertical plane) are applied to the ***Coupling 1 (Flexible Aluminum Beam Coupling)***. Figure 8 shows the failure of this coupling at a combined misalignment of 3^0 angular and 0.5 mm parallel misalignment at a running speed of 2800 rpm (46.66 Hz frequency). The center element was discovered cracked, and the fault analysis is depicted in detail in Figure.8.

The ***Coupling 2 (Elastomeric type flexible Aluminum Coupling)*** is subjected to Angular misalignment (AM)- 0 to 3^0 (horizontal plane) and Parallel misalignment (PM)- 0 to 3 mm (vertical plane).Failure occurred nearly at a combined misalignment of 3^0 angular and 2 mm parallel misalignment running speed 2800 rpm (46.66 Hz frequency), as shown in Figure 8. The fault analysis is detailed in the fish bone diagram in Figure.8.

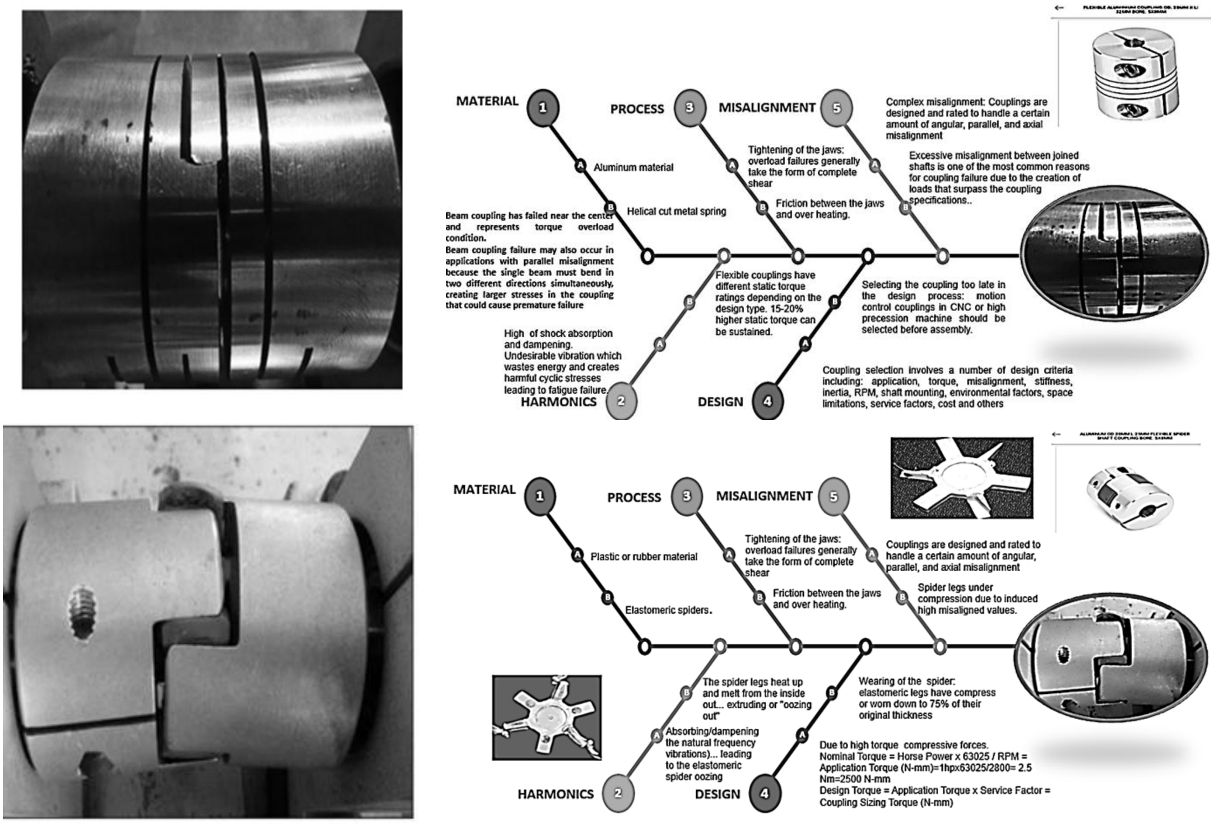


Figure 8: Fishbone Analysis for the Failure of Coupling 1 and Coupling 2

V. CONCLUSION

Final phase of experiment was carried with proposed DAS system of instrumentation to gather more meaning full data. The objective of this paper is to select a low-cost Data Acquisition System (DAS system) for industrial applications consisting of various sensors and a Data logger. The DAS was assembled with the mechanical assembly which has so many industrial analogy. As can be seen all the automation the servomotor is directly connected to the load end with the help of these high end flexible coupling. These commercially available couplings are tested for the amount of vibration level and variation in torque due to misalignment. This DAS system could be used further applied to industrial rotors for investigation of other faults like imbalance, cracked or deformed shafts, bearing defects. Furthermore, the instrumentations were tested for sensitivity under high intensity of fault induced. In terms of system validation, a comprehensive set of tests were run on both the standard (reference) system and the new DAS system. The experiment began by comparing the run-up and run-down outputs of these instruments from 500 to 2800 rpm. The vibration profiles and torque variations acquired from measurements are recorded for various types of misalignment. Based on the results, the developed measurement system is checked for robustness, dependability and accuracy.

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