INTERNATIONAL JOURNAL OF ADVANCE RESEARCH, IDEAS AND INNOVATIONS IN TECHNOLOGY

IJARIIT

ISSN: 2454-132X
Impact Factor: 6.078
(Volume 7, Issue 3 - V7I3-1629)
Available online at: https://www.ijariit.com

Condition monitoring of single-stage gear pair using vibration analysis

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ABSTRACT

In this study, an involute gear pair is designed and fabricated. A test rig is assembled to carry out the experiment in which the driving gear is subjected to different crack levels and its vibrational signatures are studied using vibrational analysis. Generation of a two-level severity root crack on the gear model for the simulation segment is done using SOLIDWORKS, and cracks of the same dimensions are replicated on the fabricated gear using a Wire-Cut Electrical Discharge Machine. The vibrational properties of the motor are then recorded under different speeds and loads for both crack severities and is compared to that of a flawless gear of same properties and dimensions. This further allows us to observe the effect of operational parameters on the vibrational properties of the motor that runs the defective gears. This study reveals the relationship between the waveforms of the vibration and crack severity of the gears along with parameters such as varying speeds and loads.

Keywords— *Gear Pair, Test Gear Assembly, FEM, Vibrational Analysis, Time Waveform, PSD, TSA, MATLAB*

1. INTRODUCTION

In industrial machinery as well as the automotive industry, Gears are most typically utilised for power transmission purposes. According to a 1978 study conducted by Allianz Versicherungs-AG, gear faults account for 65% of gear box damage. The most common type of gear faults consists of cracking, wear, pitting, scuffing, spalling (Michel & Miller, 1983).

All these rotary elements are highly susceptible to excessive vibrations. These vibrations if gone unchecked can result in severe damage to the machine and even cause injuries. Gearbox usually has vibration signals created due to meshing of teeth and gear & pinion shaft rotation. These vibration signals are specifically related to the machine but if an issue arises, these vibration signals will change. This change is useful to detect a fault before it becomes critical. The basics of Condition Monitoring is mentioned above. It is cost effective, reduces the risk of accidents by preventing total failure.

Vibration Analysis has been shown to be one of the extremely fundamental tools for condition monitoring as it is less time consuming and very convenient. The most common techniques used for waveform data processing are Time Domain Analysis (Time waveform, Time Synchronous Averaging), Frequency Domain Analysis (Fast Fourier Transform) and Spectral Analysis. Main purposes for using them are-

- To separate the relevant signals originating at the gear pair and other components, and also to reduce the noise that masks the particular signal.
- To identify the status of the gear and to differentiate and identify the faulty component.

The reason for equipping these techniques is because of the ease of measurement. Once we have processed the data, feature extraction is the next logical step for fault diagnosis to obtain information. It is well documented that the GMF and its harmonics, along with the sidebands, are a valuable component with regards to the geared vibration spectra. The increment in amplitude as well as number of any sideband is the indication of a fault and the spacing between them helps in the identification of the source. Some factors to be kept in mind regarding the identification of fault and its source in a rotating machine such as a gear pair are the rotational speed, background noise, location of the sensor etc.

2. DESIGN AND ASSEMBLY

Two different types were to be manufactured for this experiment, the driving gear will be referred to as the Gear, and the driven gear will be referred to as the Pinion. The Gear contains 24 teeth, and the Pinion contains 16 teeth, both have a module of 4.5, pressure angle of 20°. While designing gear teeth it is important to ensure slipping does not occur between the pitch circles of engaging gears, this allows for a smooth transmission of rotation from one gear to the next.

While designing the spur gear we have achieved the correct involute profile of the gear teeth, alongside the process we are supposed to accurately make the profile with the gestures of fillets and cuts as needed. The exact dimensions were achieved by following a set of guidelines/formulas/equations ensuring the geometries are correct. When we are modelling the gear in SOLIDWORKS the use of such equations is necessary. The main specifications are obtained from the table shown below, and the remaining data is obtained from the PSG Data Book.

Table 1 Detailed Specifications of Pinion and Gear

	Pinion	*Gear*
Centre distance	91.5mm	91.5mm
Module	4.5	4.5
Width	20mm	20mm
Number of teeth	16	24
Tip diameter	88mm	112.5mm
Pitch diameter	72mm	108mm
Inner diameter	30mm	30mm
Base diameter	67.65mm	101.48mm
Root diameter	68.41mm	92.25
Pressure angle	20°	20°
Root radius	1.71mm	1.2mm
Profile shift coefficient	0.8245	-0.5275

When modelling a spur gear, several rules and steps must be regarded to ensure exact geometries are made while following the governing equations.

As soon as the necessary geometries have been calculated following the governing equations, the gear can be manufactured accordingly. The first step in modelling a spur gear is drawing a circle with a specific diameter and the parametric equation is fed with the tooth angle to complete the entire profile. The involute curve originates at the base circle of the gear. The involute curve is represented with a certain set of parametric equations.

$$\text{Base Diameter: } Db = D*\cos(\varphi) \tag{a}$$

$$\text{Parametric Involute Equations: } x(t)=rb(\cos(t)+t*\sin(t)) \tag{b}$$

$$y(t)= rb(\sin(t)-t*\cos(t)) \tag{c}$$

Where Db represents the base diameter
D represents the pitch diameter
Φ represents the pressure angle
rb represents the base radius
t represents the interval over which to draw the curve.

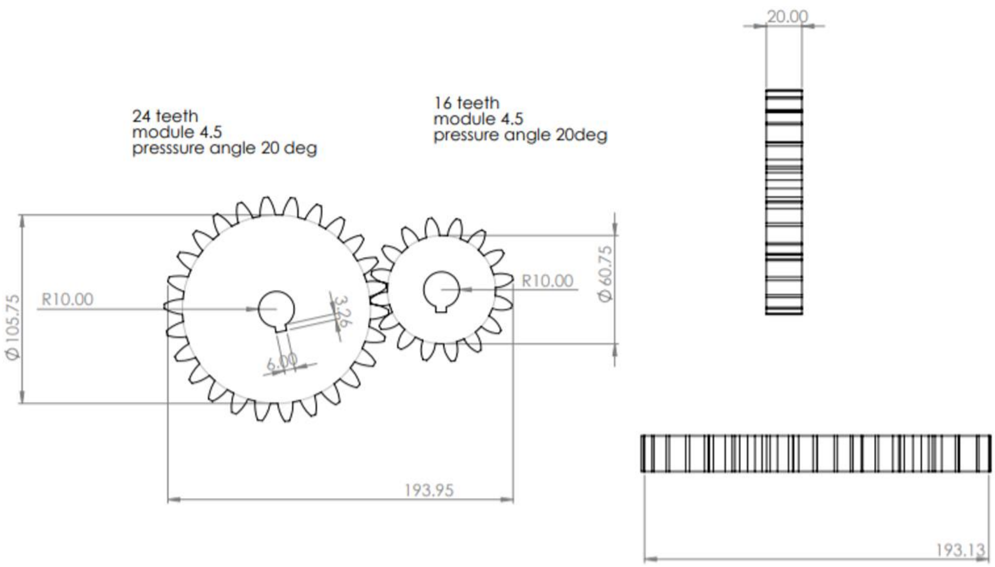


Fig. 1. Gear and Pinion Drawing

Once the external parts of the gear have been completed, the last step in modelling the spur gear is to design the internal part of the gear, which includes the bore and keyway of the gear. The bore has to be of the same diameter of the shaft to ensure a tight fit, in our case a 20mm bore should be created along with a keyway of appropriate dimensions. The same steps should be followed while designing and fabricating the pinion gear. After the gears have completed fabrication, 3 Driven gears have been kept aside to be replaced into the test rig. One gear is left flawless, while the other two gears are sent for Wire EDM cut.

Fig. 2. Wire EDM Cut of Gear

Fig. 3. Drawing of Crack models on SOLIDWORKS

Table 2 Details of Crack Induced on Gear using Wire EDM

Type of Fault	Length (mm)	Width (mm)	Depth (mm)	Angle (° degree)
Root Crack - 1	20	0.25	1.5	35
Root Crack - 2	20	0.25	2.5	35

Using the drawings obtained from the gear model created in SOLIDWORKS as reference, markings were made on the gear to help accurately reproduce the crack. WEDM is not an entirely manual process, the required length along with other details can be provided into the system in the form of code which provides us with more accurate results. The gears were then put into place, with the wire coming in contact with the root of the gear tooth at a 35° angle and code provided to generate a 1.5mm length cut was given to the first gear, and 2.5mm length cut was provided to the second gear. Once this process was completed, the dimensions were verified, and the gears were assembled into the test rig.

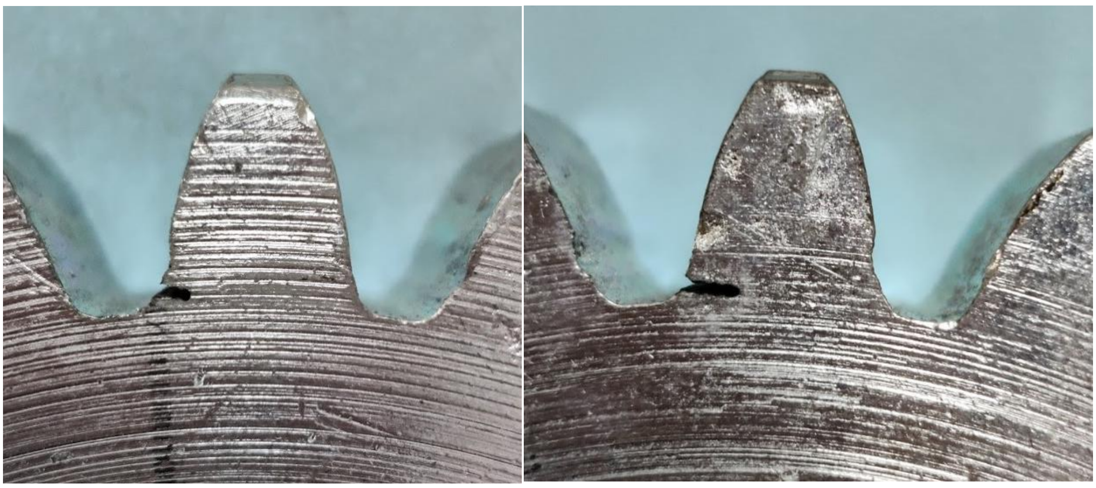


Fig. 4. 1.5mm and 2.55mm depth cut on Gear using Wire EDM

2.1 Fabrication and Assembly of Test Rig

To carry out the experimentation, a test rig had to be fabricated and assembled to simulate a working environment for the motor. The test rig consists of two parallel shafts, one which contained the Gears and the other one which consisted of the Pinions. The shafts were elevated to a height of 250 mm to accommodate the Weight plate Bearing which is used to simulate transverse load conditions onto the shaft. The Weight plate bearing fixture consists of a bearing attached to the shaft, this ensures that the outer part of the bearing does not rotate along with the shaft. The bearing is then welded to a plate below it which is used to house the slotted weights.

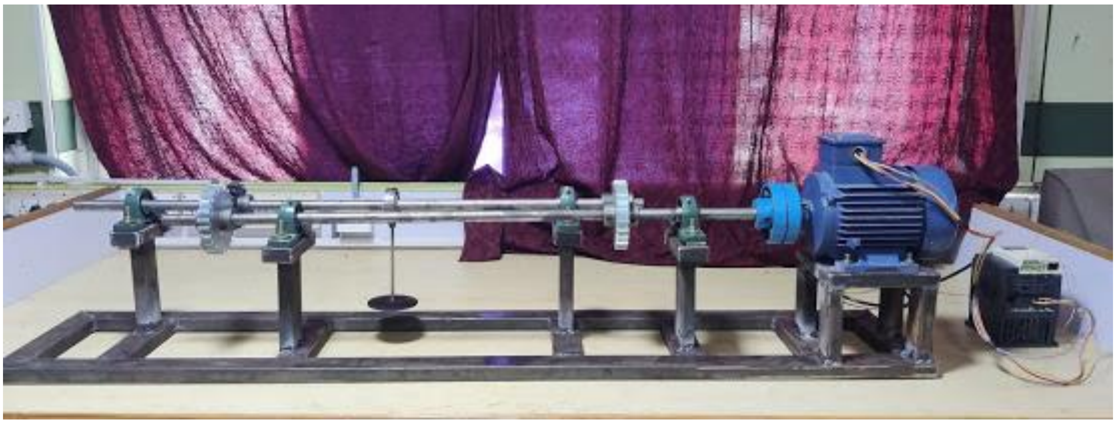


Fig. 5. Final Test Rig

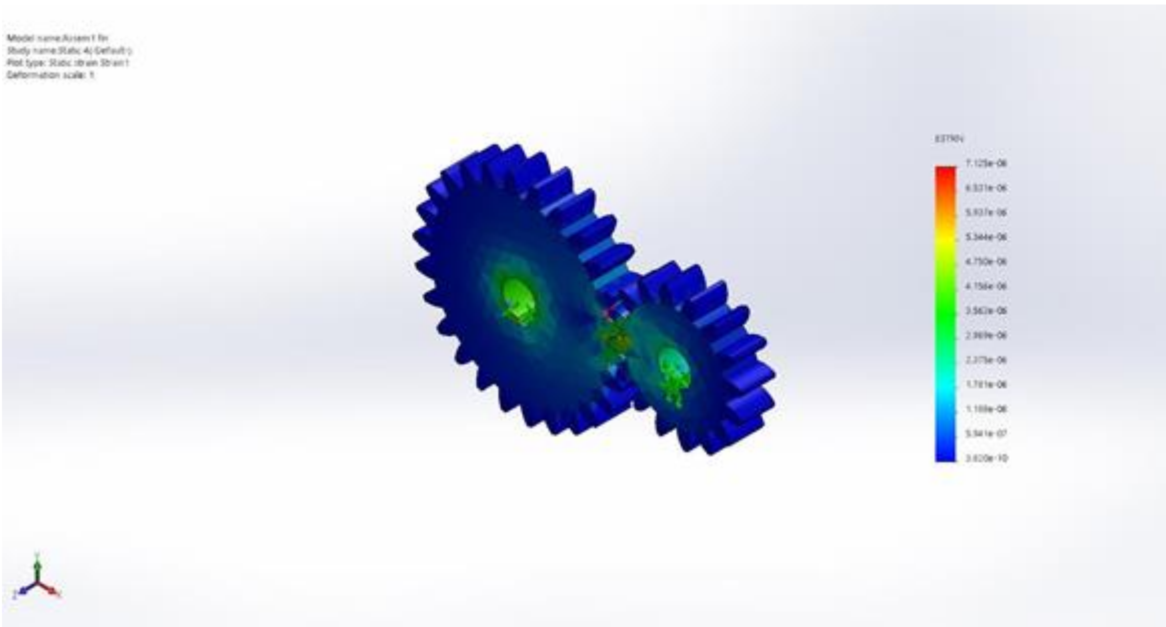
2.2 FEM Analysis

A Finite Element procedure has been developed in this work to determine the Von Mises Stress, Mean Displacement and Effective Strain to a gear pair(spur). At first, a gear pair with perfect involute is modelled using a 3D CAD Design software Solid works. The model is then introduced with cracks of respective dimensions. The generated 3D models were in turn imported to SOLIDWORKS Analysis forum to calculate the Von Mises Stress, Mean Displacement and Effective Strain by the use of FEM. The results generated were then compared with the Von Mises Stress, Mean Displacement and Effective Strain of the gear pair without inducing the crack. These results allowed us to study the stress and strain characteristics formed in the simulated models of the gears with and without crack and provided a coherent understanding of the gear properties.
to the crack length.

CASE (STRAIN)

Table 3 Strains for all Cases

	CASE 3.1(1.5mm/500rpm)	CASE 3.2(1.5mm/1500rpm)	CASE 3.3 (2.5mm/500rpm)	CASE 3.4 (2.5mm/1500rpm)
NAME	STRAIN1	STRAIN 2	STRAIN 3	STRAIN 4
TYPE	Equivalent Strain1	Equivalent Strain2	Equivalent Strain3	Equivalent Strain4
MAX	7.125e-06 Element: 1826	2.372e-06 Element: 1826	9.161e-06 Element: 10833	3.049e-06 Element: 10833
MIN	3.820e-10 Element: 4732	1.272e-10 Element: 4732	5.084e-10 Element: 11977	1.686e-10 Element: 11977



As from the given table we can infer that the maximum strain the gear with the 1.5mm crack at 500 rpm is 7.125e-06 whereas the maximum strain the gear with 2.5mm crack at 500rpm is 9.161e-06 And the maximum strain the gear with 1.5mm crack at 1500rpm is 2.372e-06, whereas the maximum strain of the gear with 2.5mm crack at 1500rpm is 3.049e-06.

Therefore, we conclude that the Equivalent Strain is directly proportional to the crack length.

2.3 Experimentation

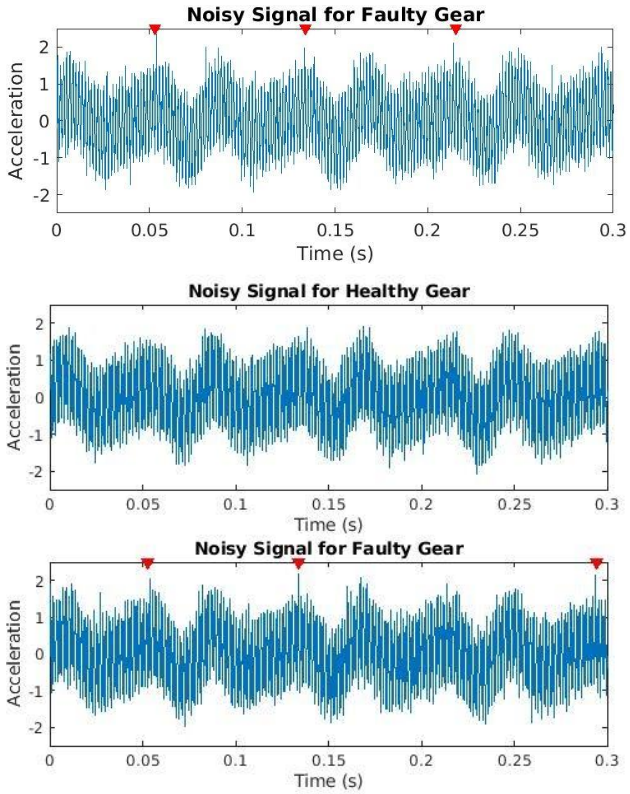
Implementing Setup: The acquisition of vibration signatures requires the use of the accelerometer and the NI DAQ working simultaneously so as to get real time data for condition monitoring. The accelerometer is placed on the bearing. The readings obtained from the accelerometer will then run through MATLAB software for analyzation and identification of faults.

3. RESULTS AND DISCUSSION

3.1 Results and Discussions

Time Waveform, Spectrum Analysis (PSD) and TSA methods were used to verify the results. Two different cases were used to gather these outputs - Once at input frequency of 25 Hz with 1.5mm root crack and once with 2.5mm root crack. For the 1.5mm crack, we experienced a 2kHz vibration signal and for the 2.5mm crack, we experienced a 8kHz vibration signal.

Time Waveform Analysis: This is a powerful and easy to use tools to locate a fault. We consider that there is just one impact per revolution since only one tooth is defected.



From the above we are able to compare the time domain plots of both the healthy and the faulty gears. In the healthy gear plots, the waveform is generally smoother and does not showcase any random peaks while in the faulty gear waveform, we can see such peaks as one rotation is completed. These peaks represent that some fault or defect is present as at that point, the gear produces high frequency oscillations during impact.

Time Synchronous Averaging: TSA is preferred to make the process of fault detection simpler. It averages out zero-mean random noise and any waveforms that aren't related with the shaft's frequencies, allowing us to separate the peaks and determine if the gear or pinion is damaged. In the plots Fig. 6 and 7, we can locate the impact on the gear waveform quite easily and the marked location has a higher amplitude as compared with the neighbouring peaks.

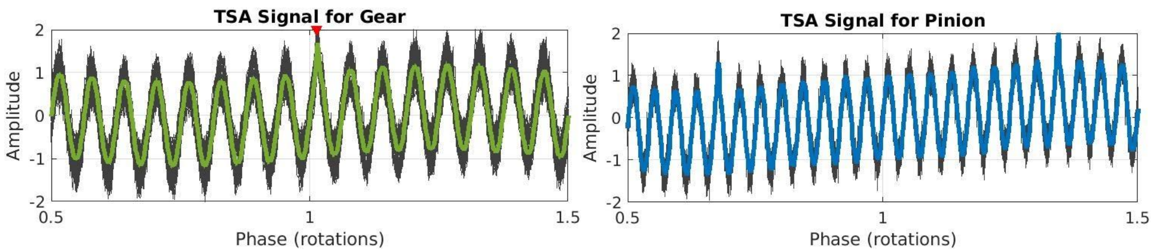


Fig. 6. Time Synchronous Averaging for Gear with 1.5mm crack and Pinion

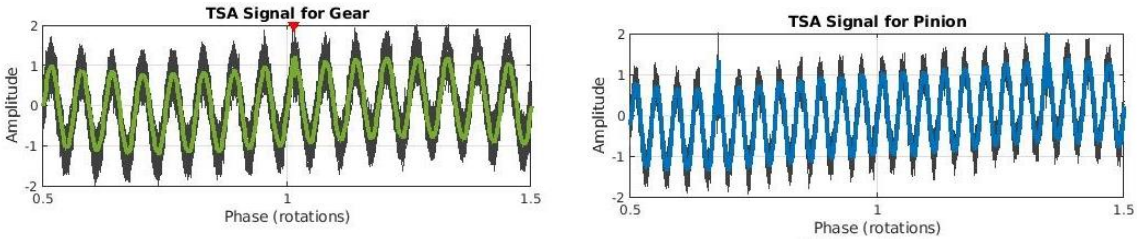


Fig. 7. Time Synchronous Averaging for Gear with 2.5mm crack and Pinion

Now that we have the TSA plots, we plot them on the power spectra with 15 gear sidebands on both the sides of the GMF. Plots related are given below.

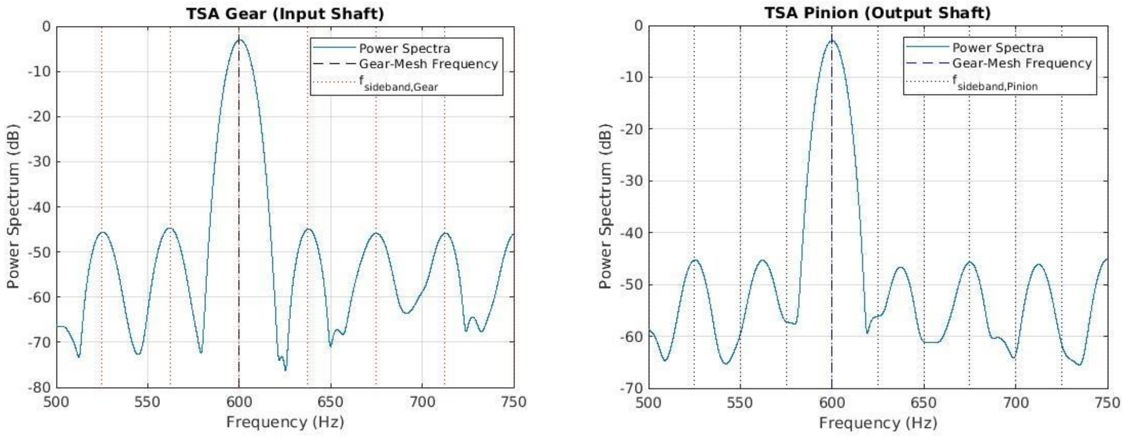


Fig. 8. On Power Spectra for a Gear and Pinion with 1.5mm crack

4. CONCLUSION AND FUTURE SCOPE

4.1 Conclusion

In this report, we worked on creating a complete test rig to test and identify faults present in a working gear pair for condition monitoring purposes. The experimental test rig was designed, fabricated, and assembled from ground up using different manufacturing techniques. Both healthy and faulty gears were used to compare the results obtained using different methods to analyse data. Finite Element Method was conducted to acquire the basic information of the gear stress, strain, vibrational characteristics under torque for both faulty gear and test gear to have a better understanding of the project and advancing with the Time Waveform and Spectral Analysis and Time Synchronous Averaging techniques. The methods used for analysing data were Time Waveform and Spectral Analysis and Time Synchronous Averaging. It was performed online using the software MATLAB. An accelerometer and a NI-DAQ was used to collect this data. The fault was successfully identified with the location. Hence, our aim was fulfilled.

4.2 Future Scope

- **Advanced Techniques:** As the technology is progressing, more and more ways are coming up to incorporate the issues arising in the vibrational analysis field. Techniques like Artificial Neural Network (ANN) and Fuzzy Logic are being studied and researched to create a more robust and efficient method wherein the signals obtained are used to extract features giving us a much better sense of the underlying faults.
- **Small Scale Industrial Implementation:** Large scale manufacturing and assembling industries where every second is precious knows that implementation of such a condition monitoring system is a must. Faults are inevitable and a non-destructive way for premature detection of fault is a great way to cut costs and remove manual labour. Small scale industries are still going for the physical methods as they are reluctant to adopt new and upcoming technologies but if properly marketed, these online condition monitoring methods can be a way for them to streamline their workings more efficiently.
- **Increase in Accuracy:** The number of transducers used and where they are positioned have a significant impact on the accuracy of the vibrational signals obtained. So, in future experimentations, instead of using a single accelerometer, three separate accelerometers can be used and placed on each of the support bearings.

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