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FABRICATION OF A TEST RIG FOR GEARBOX FAULT SIMULATION AND DIAGNOSIS

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Abstract

Gearboxes are one of the most important and widely exposed to different types of faults in machines. Therefore, manufacturers and researchers have made significant efforts to develop different fault detection and diagnostic approaches for gearboxes. However, many research foundations, such as universities, are currently working on developing different gearbox test rigs to understand the failure mechanisms in gearboxes. As a result, in this article, a gearbox testing rig was proposed and fabricated to evaluate gear performance under low-speed working conditions. It describes the primary mechanical apparatus and the measurement tools used during the experimental analysis of a multistage gearbox transmission system. The data-gathering equipment used to acquire the observed vibration data is also discussed. LabVIEW software was used to build a data acquisition platform using an accelerometer and a NI DAQ device. Then different vibration tests were conducted under different operating conditions, when the gearbox was healthy and then faulty, on this test rig, and the gathered vibration data were analyzed based on time domain signal analysis. The preliminary results are promising and open the horizon for simulating different gearbox test scenarios.

Keywords: fault detection, vibration analysis, time-domain signal, gearbox, LabVIEW

1. INTRODUCTION

Essential parts of a rotating machine include gears, rotors, shafts, bearings, etc. All of these parts are susceptible to defects when they are used. In rotating equipment, frequent fault types include imbalance, misalignment, gear, and bearing failures [1][2]. The gearbox is one of the essential parts of rotating machines that must be continuously monitored. In rotating machine systems, a condition monitoring approach can be used to determine the health of the gearbox. Regular monitoring of machine conditions is often utilized to plan effective maintenance and early identification [3]. It may be used to assess the dependability of a machine, increase its lifespan, and save maintenance costs while ensuring the safe operation of crucial devices [1]. However, it is challenging to create a mathematical model that can forecast the life of the gear due to the interplay between these variables [4]. Therefore, vibration analysis becomes a standard method for fault diagnosis in gearboxes since it can be detected by studying the vibration signal collected on the machine [5]. At times, the noise coming from the gearbox takes over. As with engine noise, this gives an erroneous idea about the gear quality. Several researchers have used the vibration signal to detect and diagnose gearbox faults. L. Guan et al. [6] used vibration data from a two-stage helical gearbox with different severity of gear damage under different operating conditions from different sensor locations. L. S. Dhamande et al. [7] developed a test rig and conducted experiments to find various flaws, including broken and missing teeth in a gearbox.

The experimental data from a single-stage gearbox are used to identify these defects. The effective statistical parameters in the faulty state for time and frequency domain analysis are successfully calculated by feeding the input signal from the FFT analyzer into the MATLAB application. The vibration analysis of gearbox defect diagnosis using the discrete wavelet transform (DWT) and statistical characteristics is highlighted by S. Suresh et al. [8]. The reconstructed signal from the wavelet coefficient was used to estimate time-domain statistical features frequently used in rotating machinery classification and fault diagnosis. These features were combined with an SVM classifier to diagnose the gearbox health status between healthy and broken tooth conditions with varying loads. It has been shown that wavelet reconstruction improves fault classification when used in fault diagnostics. Al-Arbi et al. [9] investigated the characteristics of remotely recorded vibration signals and the impact of path transmission on the effectiveness of gear fault diagnosis by analyzing two vibration signals of gears with different faults that were picked up from other locations and subjected to multiple signal processing methods. The attenuation and interference have a significant negative impact on the gear transmission signals, according to the study of data from many signals processing approaches. However, the time synchronous average (TSA) efficiently detects local gear system failures. T Praveenkumar [10] discussed the use of vibration signals for automated gearbox problem detection. The performance of the gearbox can be determined using the vibration signals. In this research, they look at both good and face wear gears to gather vibration signals to determine if the gearbox is in excellent or bad condition. Therefore, an analysis of defective and healthy gears is performed for comparison purposes.

According to previous reviews and researchers' work to detect gear faults by analyzing vibration signals, a specialized test rig that allows gear testing in a controlled environment is needed [11][12]. A test rig capable of facilitating this is required to test for different faults simultaneously. It has been observed that some researchers in this field are facing difficulty in developing and assembling a test platform that meets this purpose and may resort to using a laboratory device designed to simulate specific types of faults or using vibration signal data obtained and published by former researchers.

Therefore, this research shows how to design a platform for diagnosing gear faults using available measuring devices and tools. When looking at what was mentioned in this research paper, the researcher or specialist in this field can follow the general principles mentioned in designing a platform for testing any gear.

This research paper is organized as follows: the following section discusses the utilized mechanical and electrical equipment. It includes the gearbox to be tested and the electrical motor that is connected to the gearbox to generate the rotating motion. Section Three includes measuring the vibration signal and discusses the sensors that can be used for this purpose. After that, we talk about collecting data from sensors using a data acquisition system interfaced with a computer using LabVIEW software, which is used to analyze the vibration signal analysis and feature extraction. Section Four includes preliminary tests conducted using the proposed platform, and the results are presented and discussed. Finally, the research is concluded in Section Five.

2. ELECTRICAL AND MECHANICAL COMPONENTS

The test apparatus used vibration signal methods to keep track of a two-stage helical gearbox's health. A U-beam supported the test rig's rotating parts fixed to a concrete foundation. The beam made it simple to separate and rejoin the completed sections. The servo motor was attached to the gearbox's output shaft at one junction, where the test rig's components were coupled via flexible couplings (see Fig. 1).

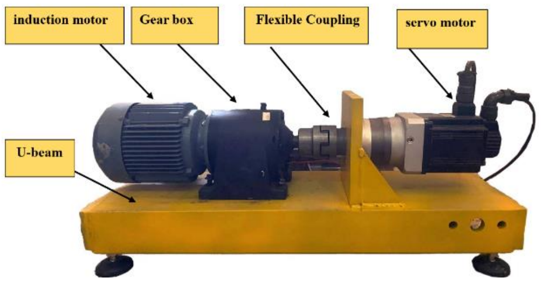

Fig. 1. Mechanical/electrical components of test rig

2.1. AC Driving Motor

An electric motor with three phases made by SEW-EURODRIVE type SA72DT90S-4, as shown in Fig. 2, was connected directly to the gearbox, where the input shaft of the gearbox is the same as the outside of the electric motor, as shown in Fig. 3. It served as the motor for the test rig and had a power of 1.1 kW (1.5 hp) at 1400 rpm, a maximum speed within a voltage range of 380 V, and an electric supply frequency of 50 Hz. It delivered maximum torque of 7.5 Nm where the motor's shaft diameter is 28 mm. A touchscreen user interface based on the programmable logic controller (PLC) is used to control the motor and configure the required test profile.

Fig. 2. SWE AC driving motor [13]

Fig. 3. Gearbox of the SEW motor [14]

2.2. Motor Speed Control

A Variable Frequency Drive (VFD) was utilized to control the induction motor's speed. The VFD is an electronic device that changes the utility power source to vary the frequency to control the AC motor at varying speeds. It is also one technique that can be used to control the speed of electrical machines or electrical generators [15]. The VFD used in this work is of type DELTA 1.5 KW, as shown in Fig. 4.

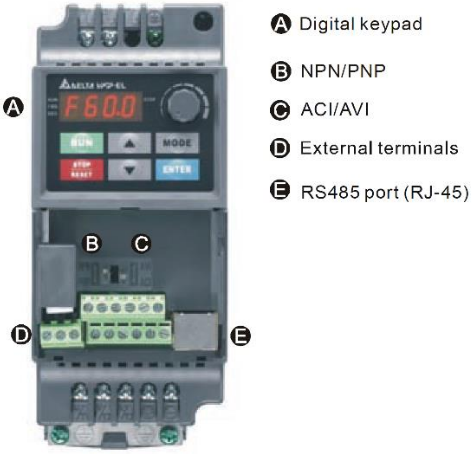

Fig. 4. Variable Frequency Drive (VFD)[16]

2.3. Two-Stage Helical Gearbox

In this test rig, a two-stage helical gearbox was used. The derived signals are more realistic and trustworthy for verification and execution when using such a commercial gearbox. Fig. 5 provides a schematic representation of the gearbox's internal architecture. The gear types in each level of the gearboxes that mesh possessing a reduction ratio based on the number of teeth are shown in the component model. Additionally, the gear mesh frequencies and rotational frequencies of each shaft within the gearbox are shown, which can be determined by:

$$fr1 = \frac{w_1}{60}$$

$$fr_2 = fr_1 * \frac{z_1}{z_2}$$

$$fr_3 = fr_1 * \frac{z_1}{z_2} * \frac{z_3}{z_4}$$

Where: w_1 is the input shaft speed in rpm (the speed of the AC motor), while fr_1, fr_2, and fr_3 are the input, intermediate, and output shafts' respective rotational frequencies.

$$fm_1 = fr_1 * z_1$$

$$fm_2 = fr_2 * z_3$$

Where the mesh frequencies for each step are denoted by fm_1 and fm_2. Table 1 shows the details of the two-stage helical gearbox.

Table 1. Details of the used two-stage helical gearbox

Description	1 stage		2 stages	
	Pinion	Gear	Pinion	gear
No of teeth				
Rotation speed (rpm)	1480	534	534	98
Meshing frequency (Hz)	541		107	
Gear ratio	2.7		5.4	

2.4. Flexible Coupling

The mechanical parts of the test rig were connected using a flexible connection. These provide flexible connectors that carry power without slipping or disconnecting while accommodating any slight misalignment between the shafts. Three-jaw couplings are used. An elastic spider rubber coupling was inserted between the coupling's two jaws. These flexible rubber spiders can only communicate the torque between the shafts. A flexible intermediate component and two partial collars make up the flexible coupling system, as shown in Fig. 6.

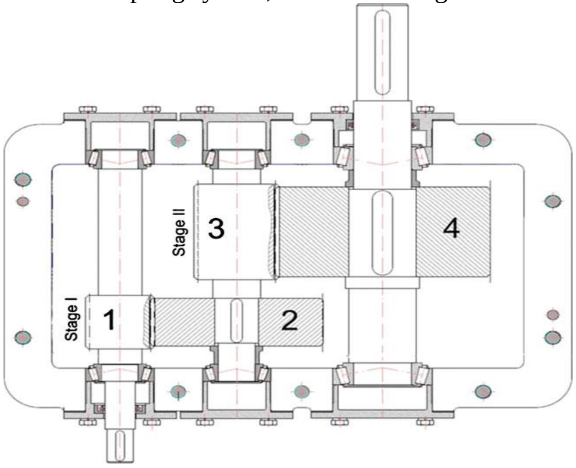

Fig. 5. A two-stage helical gearbox [17]

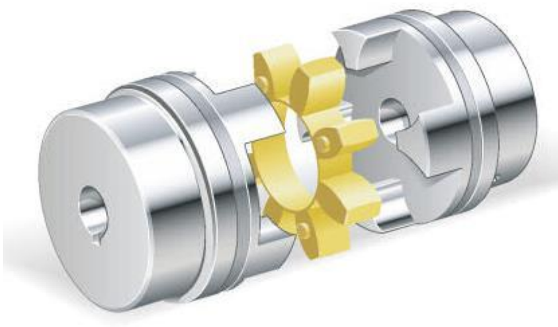

Fig.6. Flexible coupling [18]

2.5. AC Servo Geared Motor

Servomotors are drives in which the applied permanent magnets create a spinning field in the stator that drives the rotor synchronously. It has a movement that is synchronous with the applied rotating field frequency. An encoder-equipped AC servo motor is used with controllers to provide closed-loop control and feedback. This motor may be positioned accurately and regulated precisely depending on the needs of the applications. These motors often have higher tolerance designs or more robust bearings, and some simple approaches also employ higher voltages to get increased torque. A motor used primarily in CNC machines, automation, robotics, and other applications must be precise and versatile [3]. This servo motor is utilized here to generate torque that is used as an applied load on the gearbox in which we want to detect and diagnose the fault (see Fig. 7).

2.6. Load\Torque Generation

The current loop governs the motor's actions in torque mode, also known as the current mode. The servo controller takes the actual motor current from the servo drive and calculates the actual motor torque since torque is directly proportional to current. The current supplied to the motor is then changed to obtain the required torque after comparing the actual torque value with the intended torque [20]. Servo controller type ASDA-A2 delta (Fig. 8) has been used to control the torque coming out of the servo motor to represent the load on the test rig. The torque is selected according to the operating conditions required to perform the test [21].

Fig. 7. AC Servo Geared Motor [19]

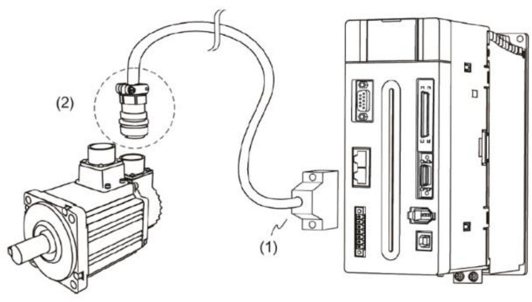

Fig. 8. ASDA-A2 DELTA controller and servo motor [21]

2.7. Programmable Logic Controller (PLC)

Most contemporary control systems utilize a Programmable Logic Controller (PLC) to manage valves, pumps, motors, and other machinery. PLCs are industrial-grade computers that can be configured to carry out control tasks. The central processing unit (CPU) and the input/output interface system are the two main components of a PLC [22], as shown in Fig. 9.

2.8. Human Machine Interface (HMI)

The employed process for communication with the PLC control system is based on computer-based Human Machine Interface (HMI) devices. HMI is a tool that enables the management, control, and visualization of device operations. The operator may operate the equipment using the touch screen or external buttons with controls and readouts graphically presented on the screen [24]. An operator's interaction with the PLC system is another way to describe HMI. In this work, PLS and HMI-type DELTA were used. The AC motor and servo drive were connected with PLS and HMI. A program has been designed to control the electric motor's speed and the torque that the servo motor delivers to the gearbox. On the touch screen, inputs (speed motor and torque from servo) and outputs (actual gearbox speed and torque on the output shaft) are shown in Fig. 10 below.

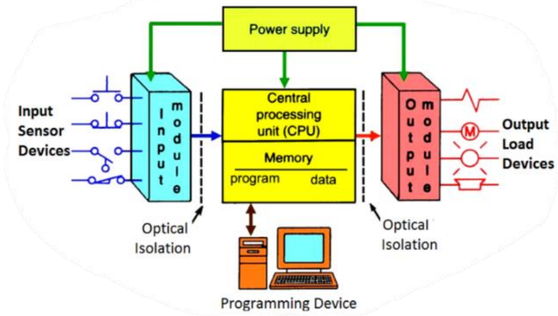

Fig. 9. PLC components [23]

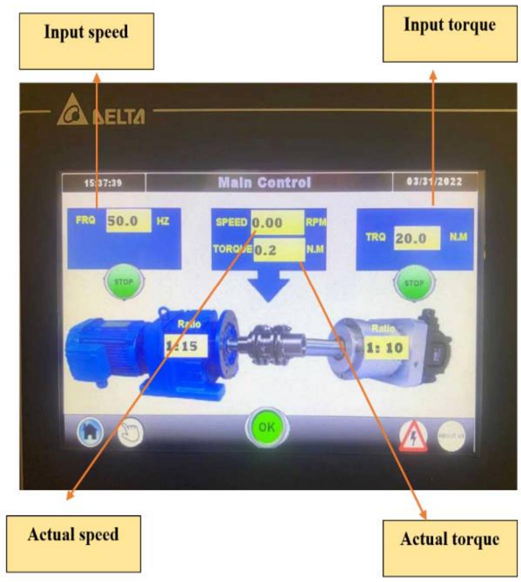

Fig. 10. Input and measured (actual) speed and torque

3. VIBRATION MEASUREMENTS

The piezo-electric accelerometer is the most popular transducer for vibration measurement, which transforms mechanical motion into a quantifiable electrical voltage output. It is a cheap, low-maintenance product that works well with mobile data collectors, analyzers, and online machine protection systems [25]. It has an extensive frequency range, up to 20 kHz, and may be used to assess dynamic changes in mechanical parts, including vibration and shock [26]. The frequency range of piezo-electric accelerometers is broad, with different sizes, shapes, sensitivities, and masses [27]. Typically, accelerometers positioned strategically on the system measure the vibration signal. In this study, the vibration coming from the gearbox was measured using a single-axis IEPE accelerometer of type CTC102-1A. This accelerometer has a standard sensitivity of 100mv/g, and the measurement range is 0.5 Hz to 15 kHz. It has a standard stud mount that has to be drilled into the gearbox's body and attached semi-permanently. The accelerometers were placed utilizing an extra bracket connected to the mounting stud on the accelerometer to avoid cutting holes in the body. Without altering the proven construction, this bracket enables wax or any other adhesives to be put to the accelerometer's bottom to secure it. The shape and specifications of the accelerometer are shown in Fig. 11 and Table 2, respectively.

Fig. 11. CTC102-1A accelerometer [28]

Table 2. Specifications of CTC102-1A accelerometer

Range of frequency	0.5 Hz to 15 kHz
Sensitivity at 5 kHz	100 mV/g
Dynamic range	± 50 g, peak
Voltage Source (IEPE)	18-30 VDC
Constant Current Excitation	2-10 mA

3.1. Data Acquisition and Analysis Software

The data acquisition software maintains the DAQ card's connection to the host computer, which also manages data collection and has necessary data analysis capabilities, including time domain and frequency domain signal analysis. Different software can be used for signal capturing and analysis, such as MATLAB and LabVIEW. The LabVIEW development environment, a graphical programming environment from National Instruments used to develop measurement, test, and control systems were used for data gathering and investigation in this research. It has built-in libraries for sophisticated analysis and data visualization and is compatible with various hardware interface devices. MATLAB software has many specialized, effective, and simple-to-use toolboxes, including the time, frequency, and time-frequency signal analysis toolboxes. Its many options help to accomplish more advanced signal analysis techniques, such as wavelet analysis. LabVIEW offer s additional MATLAB and C language capabilities, making LabVIEW's graphical programming more flexible. The generated data collection software will thus have increased ability and higher flexibility by integrating the benefits of LabVIEW visual programming and the data processing capabilities of MATLAB.

3.2. Data acquisition card (DAQ)

Data acquisition cards (DAQs) are designed to digitally alter and scale physical analog signals to match the sensitivity of the sensor or transducer. A computer with control software and data storage capacity is constantly attached to a DAQ card. The used DAQ card is of type NI USB-4431 from National Instruments. It has a 24-bit analog-to-digital converter (ADC) with four analog input channels and one analog output channel. The maximum sampling rate of this card is 102.4 KS/s per channel. The NI USB-4431 and PC communication are established through a USB interface. The front and back panels and type of this DAQ card are in Fig. 12 and 13, respectively.

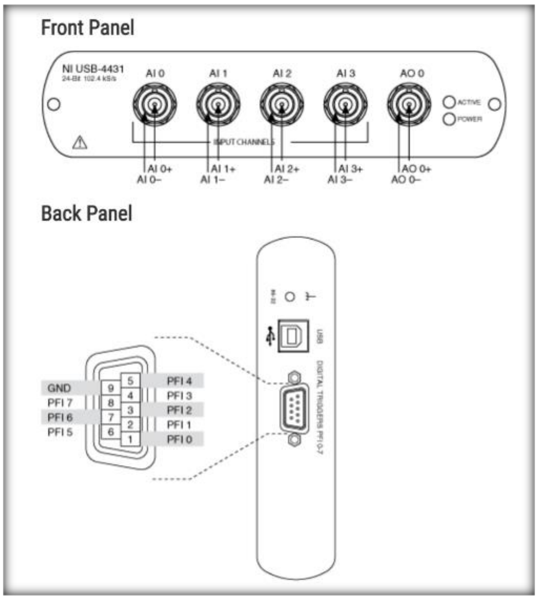

Fig. 12. The front and back panels for 4431 NI DAQ

Fig. 13. NI DAQ type 4431

4. EXPERIMENTAL TEST

Experimental tests were conducted using the developed platform in this research. In addition to the healthy condition, these tests considered different gear faults, such as broken and missing teeth. Hence, the gear faults were simulated as shown in Fig. 14, where the healthy, broken tooth and missing tooth are referred to as H, B, and M, respectively, in the forthcoming discussion. Also, to find out These operation settings are set through the touch screen on the control panel by the program that was previously explained.

A Data Acquisition System acquired the signal from the gearbox to a PC using the identified accelerometer and DAQ card. Using the LabVIEW program, a system was made to record the original vibration signals. Fig.15 shows a system for the LabVIEW program, where the vibration signal is stored, and at the same time, features are extracted from this signal. The vibration signal was acquired at three health conditions (one health and two faulty conditions). Two hundred continuous measurements were recorded for each case. The recorded time length of each measure is 0.5 seconds, and the number of data is 1024 (2^{10}) and the sampling rate is 2048(2^{11}) Hz. The raw vibration signals for the different operations and health conditions are presented in Fig.16. Results are presented for low and high operating conditions to demonstrate signal sensitivity to operating conditions and when the pinion gear is at different health status. The vibration signals presented in Fig.16 show apparent differences between the waveforms at different gear conditions for both low and high operating conditions. The signal amplitude in the low operating condition is much smaller than in the high operating condition. This shows that the operating condition significantly affects the gear diagnosis. This indicates that the test platform is working correctly and accurately recording the vibration signals, as the amplitude of the vibration signal increases with the increase in speed due to the increase in the gear mesh frequency.

Fig. 14. Broken and missing teeth in the pinion gear

Moreover, different time-domain features can be extracted from the above-measured signals to better assess the measured vibration's severity[29]–[31]. Hence, the values of the calculated root mean square (RMS) and variance (VA) for the different health statuses are shown in Fig. 17. It is clear from Fig. 16 that the features of vibration data are affected by the gear health condition in addition to the operating conditions. The RMS and VA values in low operating conditions are much lower than those in

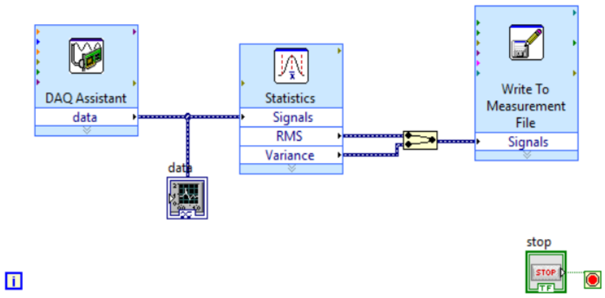

Fig.15. A simplified sample of the developed LabVIEW program

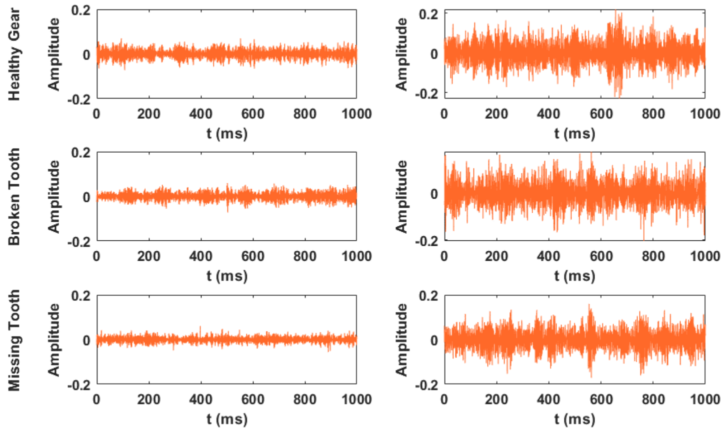

Fig. 16. Time domain vibration signals for healthy and faulty gear systems at low operating conditions (L=20%, S=40%) (Left) and high operating conditions (L=80%, S=100%) (Right)

high operating conditions. However, it is noticed that as the gear fault severity increases, the feature values decrease, which can be related to increasing the damping effect as the gap between the mating teeth increases when a tooth is partially or totally removed.

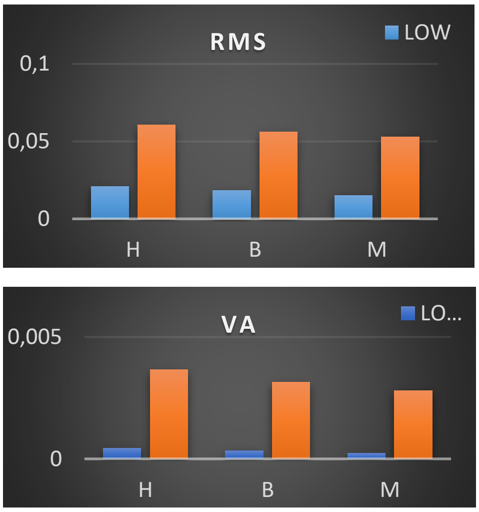

Fig. 17. Root mean square (RMS) and variance (VA) at low and high operating conditions and different health conditions

5. CONCLUSIONS

In order to evaluate the gearbox defect detection method based on vibration signal analysis, this study built an experimental test rig. Several tests were conducted to ascertain the impact of various gears' health on the severity of machine vibration. Broken and missed gear teeth were the simulated gearbox defects. The National Instruments NI DAQ 4431 and LabVIEW software-based data collecting system were utilized to capture the vibration signals. While vibrations were being measured, the gearbox was exposed to various rotational speeds and loads. By observing time domain data, vibration-based condition monitoring can find gear problems. With respect to rotational speed and load, the gears defect has different effects. Generally speaking, the developed test rig can be considered highly automated as the user does not require manual devices to measure, for example, the torque and speed of the gearbox. This is because the developed PLC control board calculates the actual speed and torque applied to the output shaft from the servo motor, which is directly connected to the gearbox shaft to be tested. Finally, this test rig will be further used to implement machine-learning techniques to detect and diagnose faults in low-speed gearboxes.

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