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INVESTIGATION OF PARAMETERS FOR FAULT DETECTION OF WORM GEAR BOX USING DENOISE VIBRATION SIGNATURE

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In industrial applications, worm gearboxes are a key element. In a worm gearbox, as the material of a worm wheel is softer than that of a worm screw, the worm wheel gear is vulnerable to failure through various modes like pitting, wearing out, or tooth breakage during the sliding process. Due to this, it is essential to monitor the failure of the worm wheel gear of the worm gearbox, and it has gained importance for the diagnosis of faults in gearboxes. The present work focuses on the investigation of the effect of worm wheel tooth breakage, worm wheel bearing outer race, and varying load on vibration signature amplitude and frequency domain statistical features such as root mean square (RMS), crest factor, kurtosis, mean, peak to peak, skewness, sample variance, and standard deviation. The experimental setup is fabricated to conduct the experimental trials. An OR34 FFT analyzer with NVGate software is used to acquire the frequency domain vibration signature. Experimental results show that captured vibration signature amplitude for healthy worm wheel and bearing increased as fault occurred on the worm wheel, and bearing and frequency domain statistical features value changed with the change in fault location in the worm gearbox.

Key words: sliding process; faulty worm wheel; faulty worm wheel bearing; frequency domain; vibration signature.

1. Introduction

Gearboxes are widely used in industry, automobiles and daily life applications to transmit power from the prime mover to the load. If any fault occurs in the gearbox, it may interrupt normal machine operation and cause a production loss. To stay competitive in the market, all industries are in search of effective and reliable maintenance strategies. Maintenance strategies can be divided into three main types: (1) breakdown maintenance; (2) preventive maintenance; (3) condition-based maintenance (predictive maintenance). Breakdown maintenance means repair work or replacement is performed only when machinery has failed.

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Preventive maintenance (scheduled maintenance) means specific maintenance tasks are performed at set time intervals in order to maintain a significant margin between machine capacity and actual duty. Condition-based maintenance (predictive maintenance) is based on an analysis of the actual state of a machine. The state of the machine can be determined by testing, inspection, or condition monitoring. Implementation of condition monitoring is cost-effective and reliable as compared to testing and inspection. Condition monitoring is the process of continuing to monitor a machinery parts in order to classify a momentous change, which is the prognostic of a progressing fault in the machinery part. Fault diagnosis of rotating machines like gear boxes of all automobiles, conveyors, escalators, presses, mining, rolling mills, blending machines, machine tools, aircraft, turbines, etc., gears, and bearings are crucial elements. Individual fault identification in gears, bearings, or the shaft of the gearbox is performed [1-6]. But a gearbox is consists of different components, viz., shaft, gears, bearing, casing, and key. The nature of the vibration signature for a fault present in multiple components of a gearbox is different from the vibration signature of a fault present in an individual component of the gearbox. There is a need to detect faults in the combination of gear and bearing in the gearbox [7]. As failure of the worm gearbox is caused by to pitting, wearing on the worm wheel, and nicks on the bearing inner and outer races, different fault conditions need to be considered when conducting fault diagnosis of the worm gearbox. As proved by research studies, fault analysis of gear pitting, wear gear, tooth breakage, bearing failures, and shaft misalignment of the gearbox can be done more reliably by vibration signature analysis [8]. These vibrations will be filtered by using the denoise method to improve the quality of the vibration signatures. By using improved vibration signatures, statistical indicators viz. mean, root mean square (RMS), standard deviation, variance, kurtosis, crest factor, margin factor, shape factor, etc. based on frequency domain are calculated. The RMS statistical indicator gives a better result as compared to other statistical indicators [9]. In condition monitoring, extracted vibration signatures from the accelerometer sensor are contaminated by background noise and vibration originating from other components of the machine [10-14]. The worm gearbox consists of a worm and a worm wheel. The advantages of a worm gearbox are that it is not bulky, construction is simpler, movement is self-locking, and backlash is low. High precision is applied in worm gearbox manufacturing. In general, the harder the worm, the greater the strength and wear resistance. Material for the worm therefore calls for a hard surface and core strength. Case-hardened steel is used for manufacturing worm. The varieties of steel used for the worm are 40C8, 55C8, 10C4, 14C6, 16Ni80Cr60, and 20Ni2Mo25. In a worm gearbox, as the material of the worm wheel is generally softer than that of the worm screw, the worm wheel gear gets pitted, or worn out, or causes tooth breakage during the sliding process [2]. The failure of the worm wheel of the worm gearbox is a matter of concern. Worm gearboxes are used in various industrial applications, viz., conveyors, escalators, presses, mining, rolling mills, blending, etc. [2, 8-9].

The novelty of this work is the, fault investigation of a worm gearbox by using a denoise vibration signature. The methodology followed in this study consists of the fabrication of an experimental test rig for fault detection of worm gearbox, the production of artificial defects produced on worm wheel and bearings, the calculation of characteristic frequencies of worm wheel and bearings, the extraction of vibration signatures by using an FFT analyser, the denoising of extraction of vibration signatures, the extraction of frequency domain statistical features, and the comparison of healthy worm gearbox vibration signature amplitude with faulty worm gearbox vibration signature amplitude.

2. Vibration data collection

2.1. Experimental test rig

The block diagram of the experimental test rig is shown in Fig.1. The experimental test rig consists of a three-phase AC motor (*0.75 kW 2880 rpm*) and a *1/15* gear ratio worm gearbox. A single-stage worm gearbox is composed of worms of double-threaded case hardened steel and profile ground, and the worm wheel has *30* teeth made of shell-cast ZCuSn12 bronze. The speed of the gearbox is controlled by a variable-frequency drive. Load applied to the gearbox by the rope brake dynamometer. The load varies from *98.1 N* to *196.2 N*. To use the vibration signature effectively and efficiently to monitor the condition of the worm gearbox, characteristic rotational frequencies are calculated for the respective loads and speeds. Then raw vibration signatures are extracted by using a uniaxial accelerometer with a sensitivity *100 mv/g* mounted in the radial direction, as shown in Fig.2 and 4-channel OR 34 Fast Fourier Transform (FFT) analyser with specifications as mentioned in Table 1 in the frequency domain. As the vibration signature extracted in the frequency domain gives better information about gearbox condition than the vibration signal extracted in the time domain [2, 8], the frequency domain signature is used for fault analysis of the worm wheel and the worm wheel bearing.

Table 1. OR 34 Fast Fourier Transform (FFT) analyser specification.

Sr.No	Parameter	Figure / Specification
1	Analysis bandwidth	*40 KHz*
2	Inputs	*4* Dynamic Inputs
3	Voltage	*10 V*
4	Frequency range	*6.4 MHz*
5	AC or DC power supply	
6	NVGate @ software	

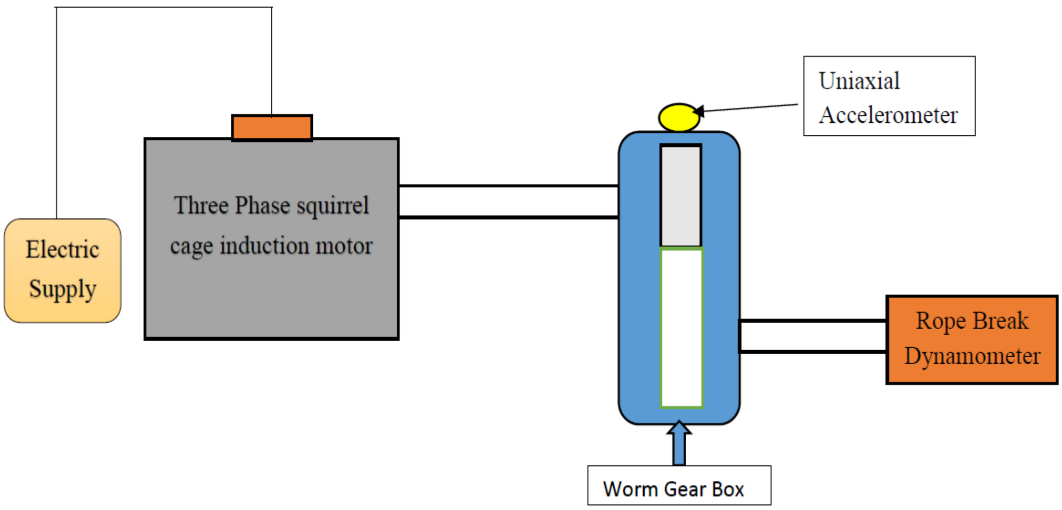

Fig.1. Block diagram of experimental testing.

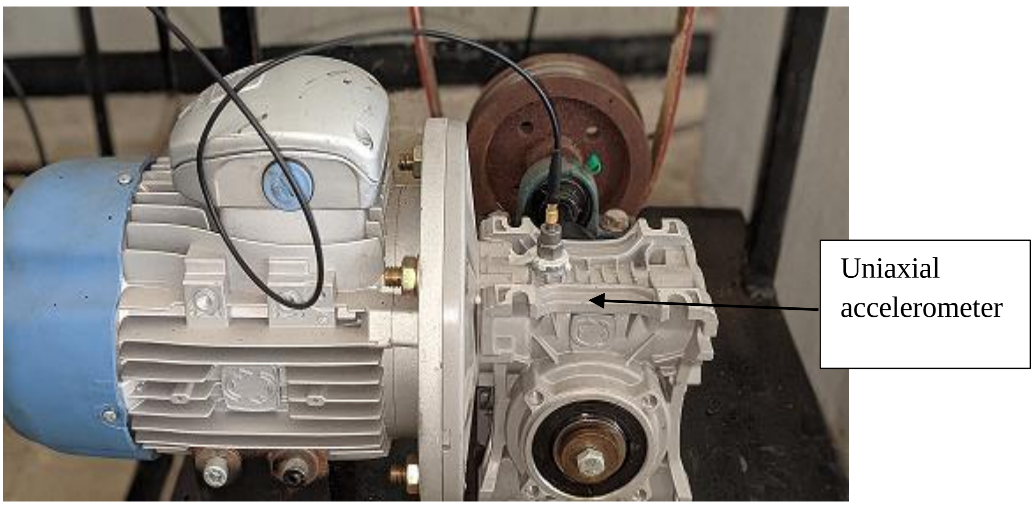

Fig.2. Mounting of accelerometer.

The vibration signature amplitude change is negligible when the accelerometer is mounted in the axial direction as compared to the accelerometer mounted in the radial direction [2, 8]. Thus, an accelerometer is mounted in a radial direction.

2.2. Fault condition of worm wheel and worm wheel bearing

The fault condition to analyse the vibration signal for the combination of gear and bearing of the worm gearbox is considered as indicated in Table 2. Fault types FT1, FT2, and FT3 are created by using grinders and wire-cutting machines as shown in Figs 3 and 4, respectively. Each trial is repeated ten times to validate the vibration signature.

Table 2. Combination of fault present in worm wheel and worm wheel bearing of worm gearbox.

Sr.No.	Condition	Description
1	Healthy worm gearbox (H)	Healthy worm wheel and healthy worm wheel bearing.
2	Fault type 1 (FT1)	Small material removal from one worm wheel tooth.
3	Fault type 2 (FT2)	Small nick on outer race of the worm wheel bearing.
4	Fault type 2 (FT3)	Combination of small material removal form one worm wheel tooth and Small nick on outer race of the worm wheel bearing.

Fig.3. Small material removal for one worm wheel tooth.

Fig.4. Small nick with circular hole on outer race of the worm wheel bearing.

2.3. Characteristic rotational frequency of the worm wheel and worm wheel bearing

To use vibration effectively and efficiently to monitor the condition of rotating machinery, it is necessary to understand the characteristics of vibration generation. The primary rotational frequencies associated with rotating elements are considered characteristics of vibration generation, which is known as the characteristics rotational frequency of rotating elements.

2.3.1. Characteristic rotational frequency of a worm wheel [14]

The gear mesh frequency of the worm wheel was calculated using the following formula:

$$f_{gm} = f_r \times n \tag{2.1}$$

where n = number of teeth, f_r = shaft rotational frequency.

If a fault occurs on a tooth surface, a vibration will be induced at this frequency.
Gear mesh frequency at an output speed of *192 rpm* is:

$$f_{gm} = \frac{192}{60} \times 30\,, \qquad f_{gm} = 96\,Hz\,.$$

2.3.2. Characteristic rotational frequency of a worm wheel bearing [14]

The main elements of rolling element bearing are the outer and inner races, the balls, and the cage. Outer raceway faults, inner raceway faults and ball faults are the main faults that occur in rolling element bearings. The characteristic rotational frequency of bearings is as follows:

$$f_{BPOF} = \frac{f_r}{2} N_b \left(1 - \frac{D_B}{D_C} \cos\theta \right), \tag{2.2}$$

f_{BPOF} = outer race elements pass frequencies,
D_C = cage diameter measured from a ball centre to the opposite ball centre,
D_b = ball diameter,
N_b = number of balls,
θ = contact angle between the bearing surfaces.

Outer race elements pass frequencies at an output speed of *192 rpm* is:

$$f_{BPOF} = \frac{192}{2 \times 60} \times 12 \times \left(1 - \frac{9.4}{54} \times \cos 0 \right),$$

$$f_{BPOF} = 15.85\,Hz\,,$$

$$f_{BPIF} = \frac{f_r}{2} N_b \left(1 + \frac{D_B}{D_C} \cos\theta \right), \tag{2.3}$$

f_{BPIF} = inner race elements pass frequencies.

Inner race elements pass frequencies at an output speed of *192 rpm* is:

$$f_{BPIF} = \frac{192}{2\times 60}\times 12\times\left(1+\frac{9.4}{54}\times\cos 0\right),$$

$$f_{BPIF} = 22.54\,Hz\,.$$

3. Vibration signature measurement by the OR34 FFT analyser

Vibration amplitude in terms of acceleration is measured with the help of an OR 34 FFT analyser and uniaxial accelerometer and converted into velocity as an ISO vibration severity chart uses vibration amplitude in terms of velocity. The sampling frequency used is *20000 Hz*. The setup is run for *60* seconds and vibration signatures are acquired after attaining a stable condition. Initially, the readings are collected from the healthy condition of the worm gearbox. A healthy worm wheel is replaced by a faulty worm wheel with small material removal form which one worm wheel tooth is placed. Vibration signals are measured in the frequency domain, as shown in the figure. In the next set of experiments, vibration response are measured for fault type 2 (FT2) and fault type 3 (FT3). All vibration signatures are extracted in the frequency domain, are as shown in Figs 5, 6, 7, and 8.

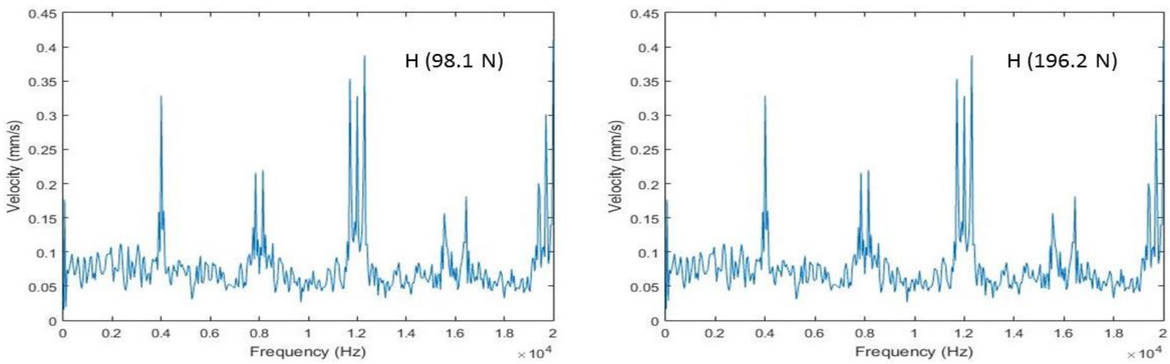

Fig.5. Extracted raw vibration signature for H.

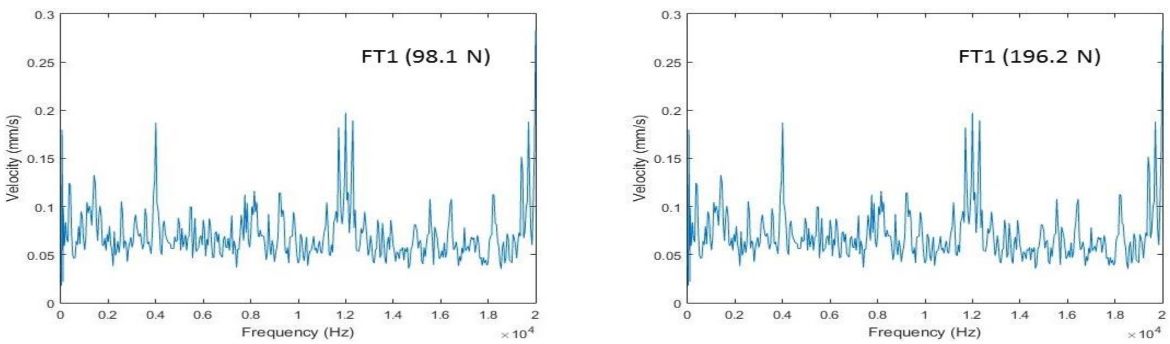

Fig.6. Extracted raw vibration signature for FT1.

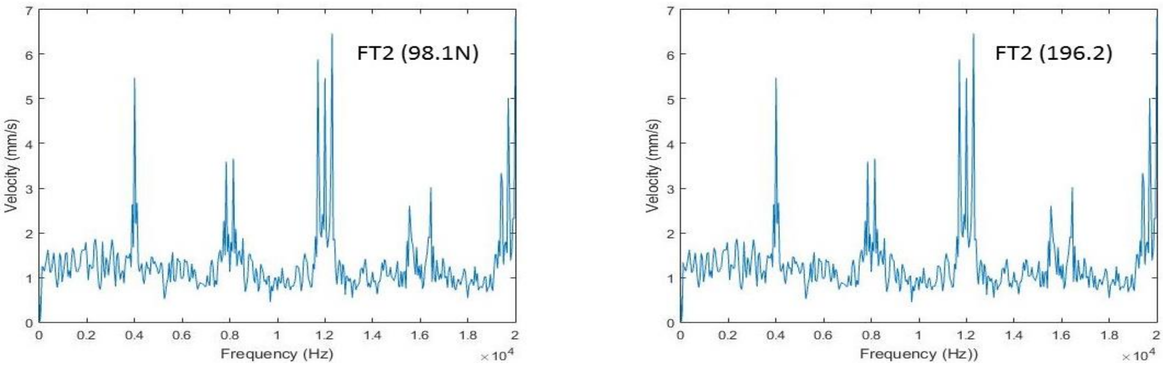

Fig.7. Extracted raw vibration signature for FT2.

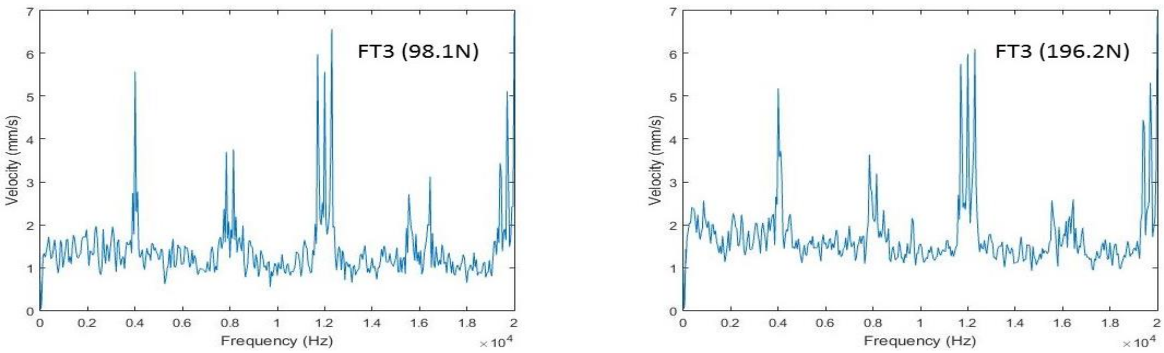

Fig.8. Extracted raw vibration signature for FT3.

4. Denoising of the vibration signal

In signal processing, denoising is a method that is used to reconstruct a vibration signal from a contaminated signal. Its aim is to remove noise and preserve useful information. In condition monitoring of rotating machinery, extracted vibration signatures from the accelerometer sensor are contaminated by background noise, electromagnetic interference, and vibration originating from other components of the machine, such as the motor and the data acquisition system. Therefore, the initial task of fault analysis is to separate the actual mechanical vibration signal from the contaminated signal. In this research, contaminated vibration signatures are denoised using NVGate software.

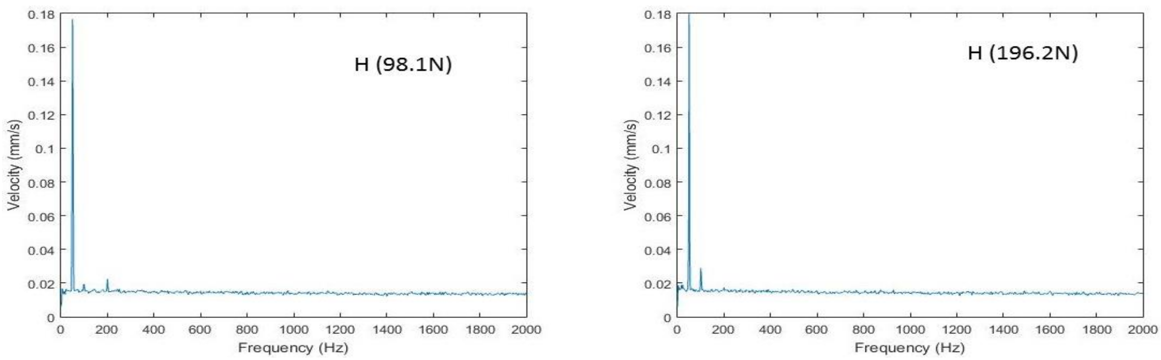

Fig.9. Denoise vibration signature for H.

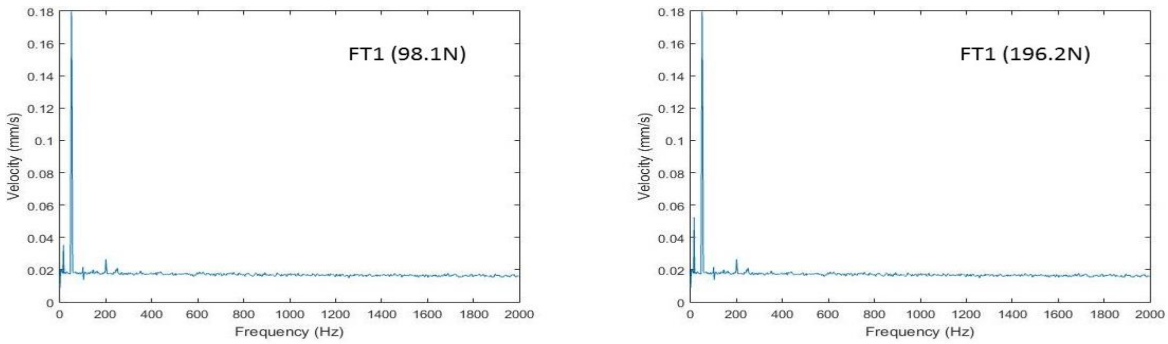

Fig.10. Denoise vibration signature for FT1.

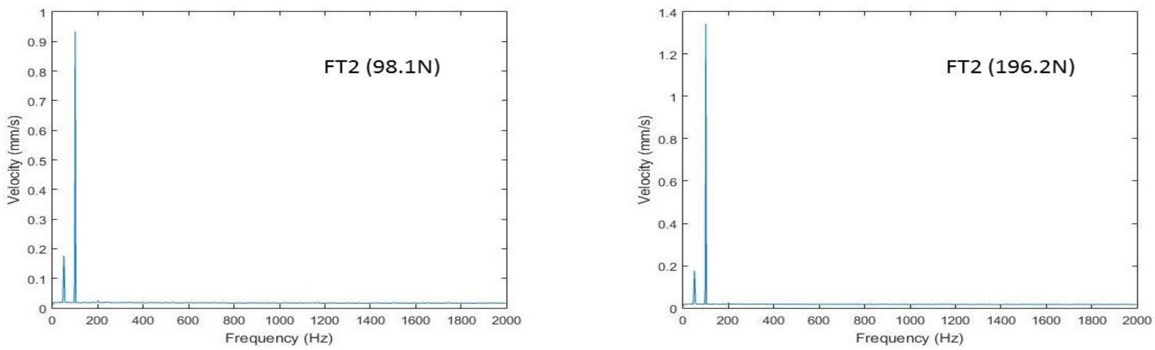

Fig.11. Denoise vibration signature for FT2.

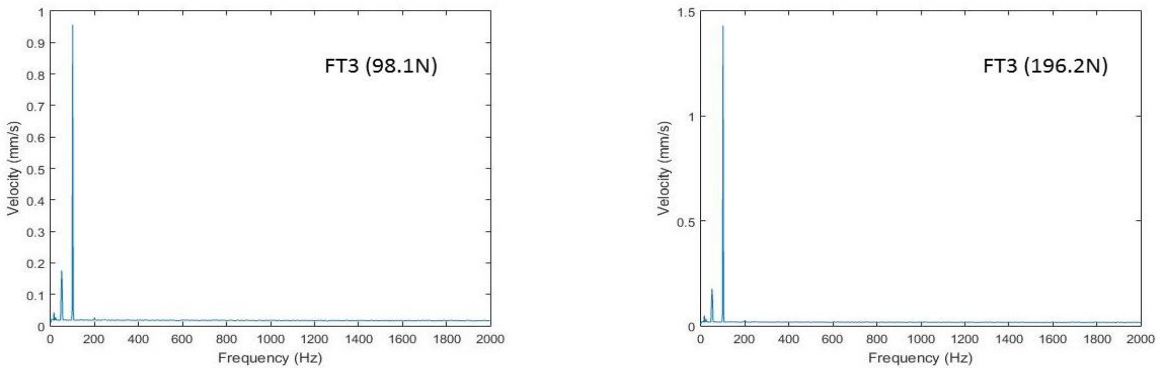

Fig.12. Denoise vibration signature for FT3.

For analysis of FT1, FT2, and FT3, the denoise vibration amplitude of FT1, FT2, and FT3 was compared with the denoise vibration amplitude of the healthy worm gearbox at the gear mesh frequency of the worm wheel (f_{gm}) and the outer race elements pass frequency (f_{BPOF}) for loads *98.1 N* and *196.2 N*. As shown in Fig.9, Fig.10, Fig.11 and Fig.12 for loads *98.1 N* and the *196.2 N*, denoise vibration amplitudes of FT1, FT2 and FT3 at the outer race elements pass frequency and the gear mesh frequency of the worm wheel increase, respectively. When a faulty worm wheel is combined with a faulty bearing outer race, the vibration amplitude increases at both frequencies. With a fault present in the worm gearbox, vibration amplitude increases with an increase in load. When a fault is present on the bearing outer race, there is a slight change in the vibration amplitude of the worm wheel at the gear mesh frequency, and when the worm wheel is faulty, there is no change in the vibration amplitude of the bearing at the outer race elements pass frequency. In the frequency domain, eight statistical features such as RMS, crest factor, kurtosis, mean, peak-to-peak, skewness, sample variance, and standard deviation are extracted. Variations in statistical features are shown in Figs 13 and 14.

Fig.13. Variation of statistical feature for *98.1 N*.

Fig. 14. Variation of statistical feature for 196.2N

When only the worm wheel bearing the outer race is faulty, crest factor, kurtosis, and skewness show less value as compared to a healthy worm gearbox. On the other hand, for FT2, FT3 shows greater value as compared to a healthy worm gearbox. Therefore, in the case of a worm gearbox, the crest factor, kurtosis, and skewness are strong predictors that the worm wheel bearing outer race is faulty. RMS, mean, peak-to-peak, sample variance, and standard deviation value increase with change in fault location in the worm gearbox. All statistical feature values increase with the respective applied load, as shown in Figs 13 and 14. As per past research, crest factor, kurtosis, mean, peak to peak, skewness, sample variance, and standard deviation values depend on RMS [2, 4, 7]. RMS is considered for further fault analysis of the worm gearbox by using the design of the experiment based on response surface methodology.

5. Conclusion

Faulty outer race bearings, small tooth removal from the worm wheel, and a combination of faulty worm wheel bearings investigated in this paper by using a denoise vibration signature. Based on the experimental results, subsequent conclusions have been drawn:

1) The experimental setup fabricated for fault detection of the worm gearbox is functioning satisfactorily.
2) After denoising, vibration amplitude in the frequency domain corresponding to the gear mesh frequency of the worm wheel and outer race elements pass frequency increases with a change in the worm wheel and worm wheel bearing condition.
3) With a fault present in the worm gearbox, vibration signature amplitude increases with an increase in load.
4) When a fault is present on the bearing outer race, there is a slight change in the vibration amplitude of the worm wheel at the gear mesh frequency. Similarly, when the worm gear is faulty, there is no change in the vibration amplitude of the bearing at the outer race elements pass frequency.
5) In the case of a worm gearbox, crest factor, kurtosis, and skewness are strong predictors that the worm wheel bearing outer race is faulty.
6) Extracted statistical features vary with the change in fault location in the worm gearbox. Also, statistical features increase with the respective applied load.

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Nomenclature

D_C – cage diameter measured from a ball centre to the opposite ball centre, mm
D_b – ball diameter
f_{BPOF} – outer race elements pass frequencies, *Hz*
f_{BPIF} – inner race elements pass frequencies, *Hz*
f_{gm} – gear mesh frequency, *Hz*
f_r – shaft rotational frequency, *Hz*
N_b – number of balls,
n – number of teeth
θ – contact angle between the bearing surfaces, degree.

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