Detection and Identification of Gear Teeth Damage through Sound and Vibration Signal Analysis of Austempered Ductile Iron Gear

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Abstract - *Gearbox is a key part of any machinery and to make sure it runs at peek condition it is subjected to condition monitoring. The purpose of this project is to study vibration and sound characteristics for austempered ductile iron (ADI) gear. The experiment is conducted for healthy and faulty gears at various loading condition and speed. The gear fault selected for this experiment is broken teeth. The data is collected with the help of data acquisition system (DAQ). The input to DAQ are accelerometer, microphone, order tracking devise and impact hammer. The output of the DAQ is connected to the system. The procedure for finding the defective gear in a gearbox is by compare the data acquired of the gearbox with healthy and defective gear. The data is collected and processed using time domain analysis, frequency domain analysis, angular domain analysis (order analysis) and sound analysis. The result for broken teeth shows the increase in vibration amplitude at 1st gearmesh frequency (GMF) with the presence of natural frequency both in Fast Fourier transform (FFT) and order analysis. The periodic change in amplitude of vibration in time domain can also act as a solid evidence for broken teeth. The sound analysis data is represented using 1/3 octave which shows the increase in sound pressure level when the faulty gear is present in gearbox.*

Keywords: Fast Fourier Transform (FFT), Order analysis, 1/3 Octave analysis, Gear mesh frequency (GMF), Austempered ductile iron (ADI).

1. INTRODUCTION

The gearbox plays an important role of power transmission in any system. So, any defect in gearbox will lead to lower efficiency in power transmission and will lead to lower productivity. To avoid this the gearbox is keep under continuous condition monitoring. So, if there is any change in vibration or sound level it can easily be studied and proper action can be taken to keep the efficiency of the gearbox high. In this experiment the gear material selected is austempered ductile iron (ADI) and the defect is two broken teeth. ADI has better yield and tensile strength than steel. Generally, cast iron has high damping capacity and absorbs noise and vibration due to the presence of graphite particles [1]. ADI also has an exceptional combination of high tensile strength with good ductility and toughness [2]. And keeping the austempering temperature between 250°C to 350°C will yield maximum hardness [3]. In the present experimental setup FRF is conducted to find the natural frequency of the gear, accelerometer is used to measure the vibration amplitude, order analysis is used to measure speed, microphone is used to record sound pressure level and all this is connected to DAQ which in turn is connected to laptop. The experiment is conducted for varying speed and torque. The collected data is then analyzed using time domain analysis, frequency domain analysis, order analysis and sound analysis. The time domain analysis gives clear indication of defect related to broken teeth [4]. The increase in sideband amplitude of defective gear when compared to healthy gear is proof of defect in gear [5]. And the presence of high 1X GMF with natural frequency indicated the defect is broken teeth [6].

2. METHODOLOGY

2.1 Gear

The gear material used in the experimentation is austempered ductile iron. The gear was cast as per the percentage weight composition provided in table 1. Then the cast is machined as per the specification of table 2. The machined gear is then subjected to two step heat treatment. The first stage is austenitizing in which the cast is held at 900˚C for 2 hours. The second satge is called austempering where in cast is quenched rapidely using a salt bath. The cast is kept in this salt bath for 2 hours at 270˚C. The difference in hardness before and after heat treatment is tabulated in table 3.

Table-1: Percent weight composition

Material	C	Mn	Si	Cr	Cu	Mg
ADI 2	2.8	0.4	2.4	0.02	0.6	0.03

Table-2: Specification of gear pair

Parameter	Gear	Pinion
Number of Teeth	45	28
Module (mm)	2.5	
Pressure Angle (Deg)	20	

Face Width (mm)	25	
Pitch Circle Diameter (mm)	112.5	70
Center Distance (mm)	91.25	

Table-3: Gear Hardness

Gear Material	Gear (HRC)	Pinion (HRC)
Ductile cast iron	52.033	50.9
Austempered Ductile Iron	65.63	66.73

Fig -1: Healthy ADI gear set

Fig -2: ADI gear with removed teeth

2.2 GEARBOX

The gearbox test rig used to conduct this experiment is power recirculation type. The test rig mainly consists of a motor to rotate the gearbox, a load coupling to apply load on to the gearbox and a set of gearboxes assemble. The test gears are fitted at test gearbox as shown in figure 3. The figure 4 shows the setup used to conduct the experiment.

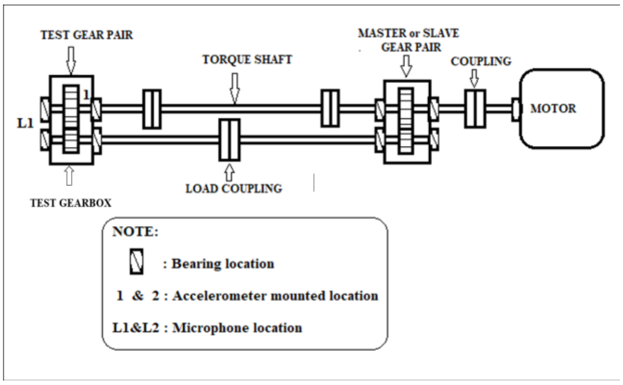


Fig -3: Schematic representation of gearbox test rig.

Fig -4: Experimental setup of gearbox test rig.

2.3 EXPERIMENTAL PROCEDURE

The following steps are used for the experimental procedure;

1. Natural frequency of the gear is found using FRF uing impact hammer setup.
2. Accelerometer is used to collect vibration data, Order tracking device is used to collect rotational speed data and microphone is used to collect sound data.
3. DAQ is used to collect data from all the inut devices. The data is then transferred from DAQ to computer.
4. The data is collected for healthy and faulty gear.
5. Vibrosoft software is used to to record, save and post-process the data.
6. The data is interpeted in time domain, frequency domain (FFT), angula domain (order) and as sound pressure level.
7. The data of healthy and faulty gear are compared to find defect patterns.
8. The experiment to repeated for combination of different rpm (200rpm – 900rpm with increments of 100rpm) and torque (0, 5Kg - 20.8463 Nm and 10Kg - 41.6925 Nm).

3. RESULT AND DISCUSSION

3.1 FREQUENCY RESPONSE FUNCTION

FRF technique is used to find the natural frequency of the gear using impact hammer method. The first 6 natural frequency are 37Hz, 41Hz, 91Hz, 104Hz, 185Hz and 197Hz. It should be noted that the natural frequency should be taken in places where there is 180˚ phase shift and coherence value is above 0.8.

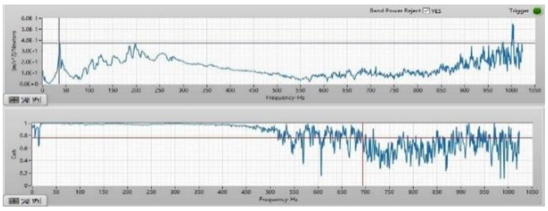


Fig -5: Magnitude and Coherence

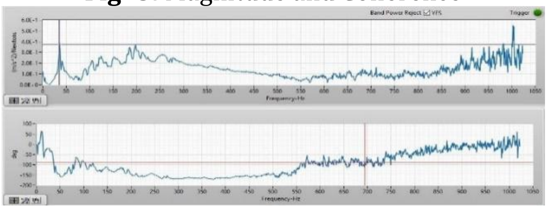


Fig -6: Magnitude and Phase angle

3.2 TIME DOMAIN ANALYSIS

All data collected is primarily recorded in time domain format. The use of time domain analysis in fault detection comes when we have broken teeth.

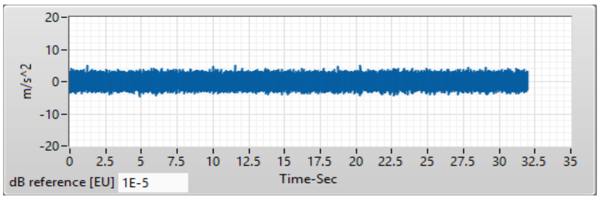


Fig -7: Typical time domain data of healthy gear

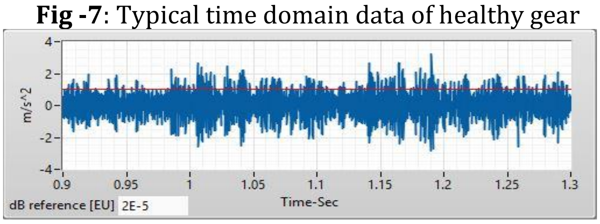


Fig -8: Typical zoom time domain data of healthy gear

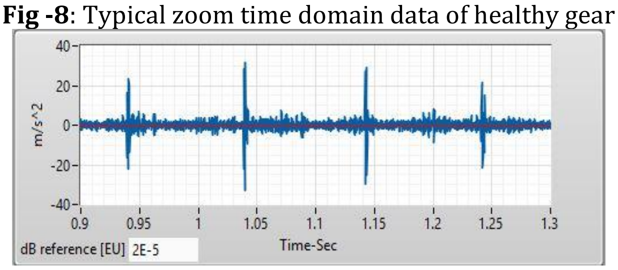


Fig -9: Typical zoom time domain data faulty gear for 296rpm.

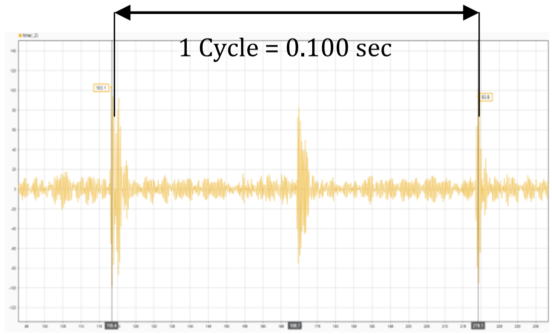
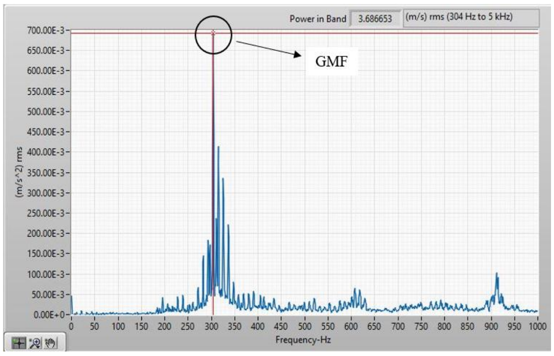


Fig -10: Time domain data faulty gear for 600rpm

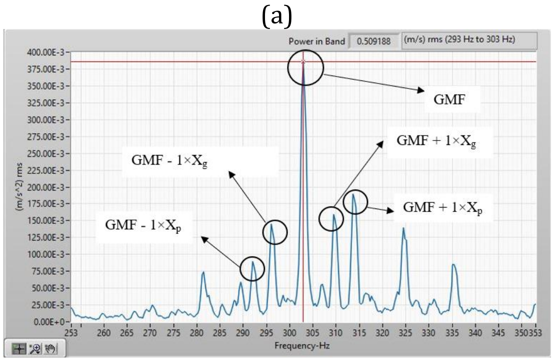
The time taken to complete one cycle for 600rpm is 0.100 sec (Note: 600/60 = 10 Hz; 1/10Hz = 0.100 sec.). The figure 8 and 9 shows that there is periodic peek at an interval of 1 cycle. When comparisons is made between the faulty gear and healthy gear the presence of peeks in faulty gear is clearly visible.

If we further look into the time domain data of faulty gear (figure 10) we can see that there is a 2nd peek between the cycle. So, for every cycle there is two peeks which leads to the conclusion that there are there are two broken teeth. The spacing between there two peeks are equal this shows that they are opposite to each other.

3.3 FREQUENCY DOMAIN ANALYSIS



(a)



(b)

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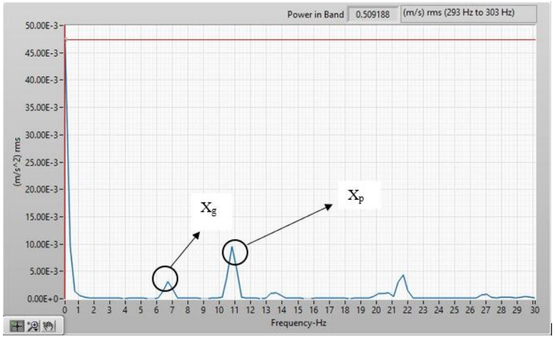


(c)

Fig -11: (a)Typical FFT spectrum of healthy gear, (b) Zoomed FFT spectrum near 1st GMF, (c) Zoomed FFT spectrum near gear and pinion rotational frequency.

Frequency domain analysis is done using fast Fourier transform (FFT). In a Typical FFT four fundimental frequency of gear analysis can be observed. Gearmesh frequency (GMF) in figure 11(a), Sidebands of GMF in figure 11(b), Rotational frequency of gear and pinion in figure 11(c) and last is natural frequency which is visible when there is defect figure 13.

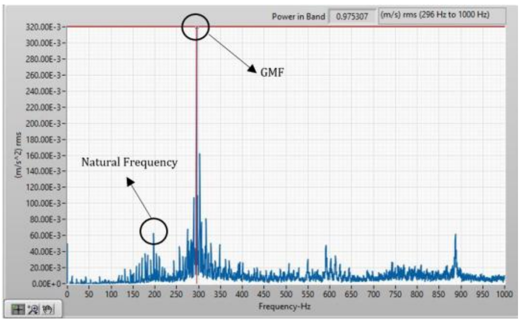


Fig -12: Defect gear FFT spectrum for 393.661rpm at 41.6925 Nm

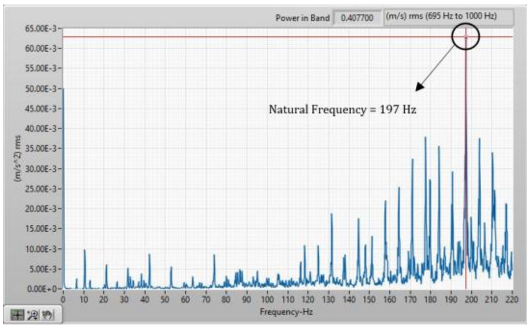


Fig -13: Zoomed defect gear FFT spectrum for 393.661rpm at 41.6925 Nm

The figure 12 and 13 represent Defect gear FFT spectrum for 393.661rpm at 41.6925 Nm. In figure 11 there are two peeks one representing GMF = 295.24575 Hz and the other natural frequency. In the zoomed spectrum of figure 13 the natural frequency is clearly visible at 197 Hz.

The presence of High 1st GMF with natural frequency indicates the presence of broken teeth defect.

The figure 14 shows that the amplitude of vibration for broken teeth gear is more than that of the gear with no defect for majority of cases. There is also increase in vibration as we increase load and RPM.

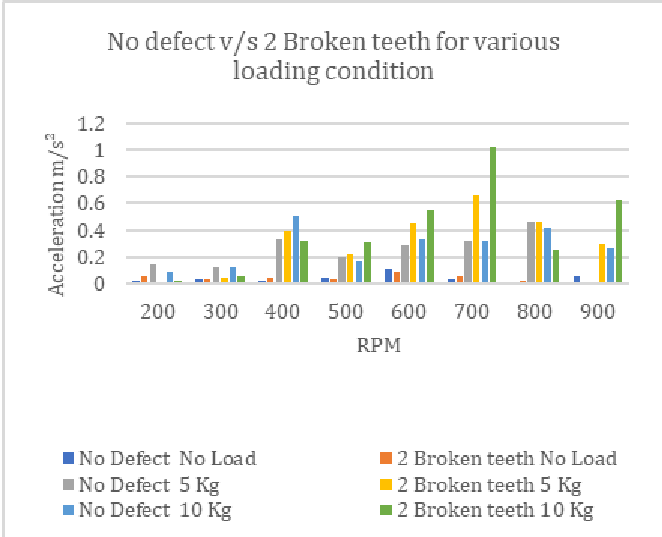
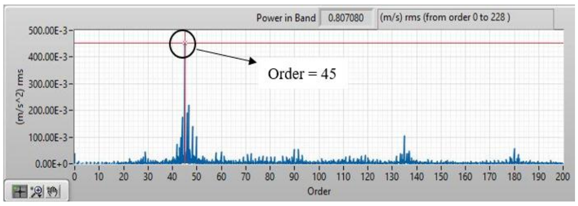
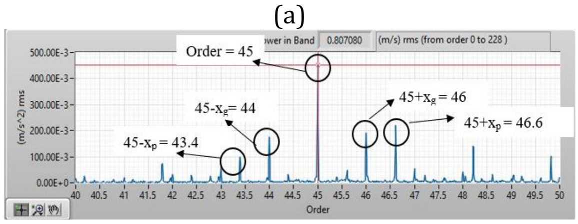


Fig -14: No defect v/s 2 broken teeth for various loading condition

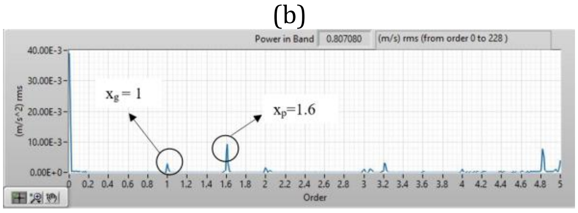
3.4 ORDER ANALYSIS



(a)



(b)



(c)

Fig -15: (a)Typical order spectrum of healthy gear, (b) Zoomed order spectrum near 45th order, (c) Zoomed order spectrum near gear and pinion rotational frequency.

Order is defined as number of cycles per revolution. 45th order represents gearmesh frequency (GMF) and the we see its harmonics in term of 90th 135th etc…

In figure 15 (c) the 1st order is representating the running speed of gear. 45th order has sidebands that represent at 45th Order $\pm$ Xg , 45th Order $\pm$ Xp. Where Xg = Order of gear (running speed of gear) and Xp=Order of pinion (running speed of gear).

1^{st} order = $rpm\ /60$

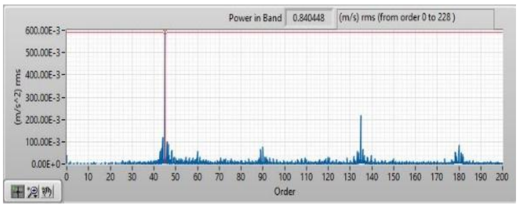


Fig -16: Order spectrum of healthy gear for 404rpm at 41.6925 Nm

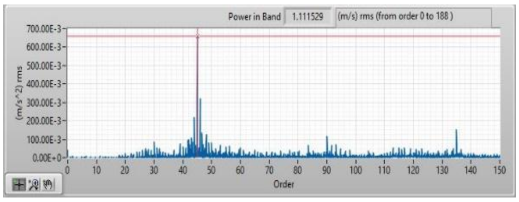


Fig -17: Order spectrum of faulty gear for 393.661rpm at 41.6925 Nm

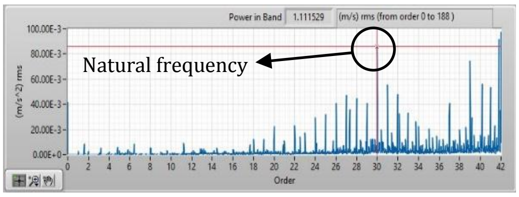


Fig -18: Zoomed order spectrum of faulty gear for 393.661rpm at 41.6925 Nm

For 393.661rpm;
01^{st} order = 393.661 /60 = 6.5610 Hz
30^{th} order = 6.5610 × 30 = 196.83 Hz
45^{th} order = 6.5610 × 45 = 295.24 Hz

In figure 17 and figure 18 we can see there is peek at 30^{th} order which is equivalent to 196.83 Hz. 197 Hz represented natural frequency according to FRF conducted earlier.When the comparasion is made of figure 16 and figure 17 we can clearly see increase in amplitude of vibration from 0.5935 m/s^2 to 0.66141 m/s^2, this shows that the defect in gear lead to higher vibration.

The presence of natural frequency due to excitation from the defect and hight amplitude of vibration in 45th order indicated the presence of teeth broken defect.

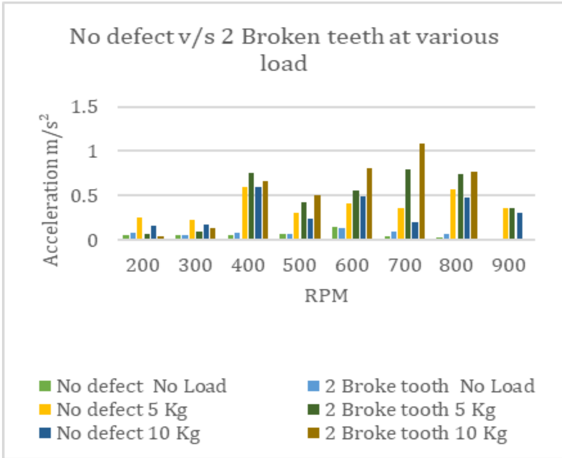


Fig -19: No defect v/s 2 broken tooth at various loads

The result shows that in most cases there is signification increase in acceleration value when compared between no defect 45^{th} order spectrum and with defect 45^{th} order spectrum.

3.5 SOUND ANALYSIS

The operating procedure of sound analysis is same as that of vibration analysis. The data collected for healthy gear and gear with 2 missing teeth for various loading condition. It is observed that the noise level is constantly about 95 dB(A) which is considered harmful for human ear if exposed to long hours. Noise signal analysis are to be conducted in controlled environment for eliminate the influence of surrounding noise effects.

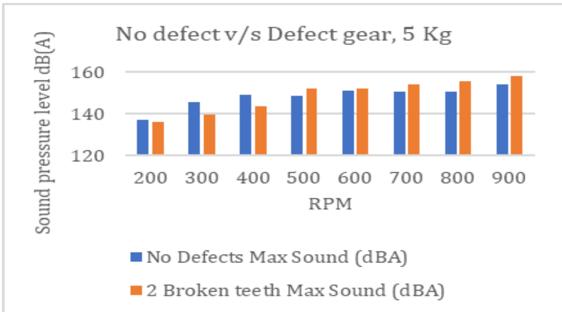


Fig -20: No defect v/s Defect gear, 5 Kg

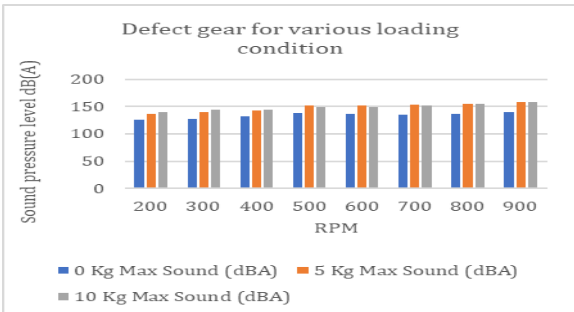
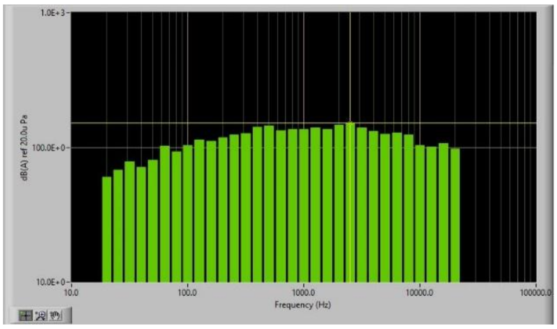


Fig -21: Defect gear for various loading condition


(a)

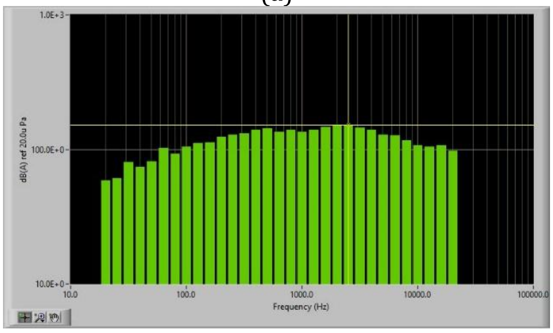

(b)

Fig -22: Sound pressure level for 600 RPM, 5Kg load, in 1/3 octave sound analysis (a) Healthy gear (b) Faulty gear

When the comparision is made between healthy and faulty gear for various running speeds there is increase in sound pressure level for faulty gear from 500rpm (figure 20). The figure 21 shows the increase in sound pressure level when load is applied to faulty gear. Also, the increase in sound pressure level for 5kg to 10 kg is very low.

4. CONCLUSIONS

The following conclusions are drawn from the present work.

1. Time domain analysis is most helpful while finding the broken teeth defect.
2. The increase in amplitude of vibration when we compare the healthy and faulty gear indicates to presence of defect.
3. The presence of 1X GMF and natural frequency is a clear indication of broken teeth defect.
4. The defect pattern which includes 1X GMF and natural frequency peek can be observed in both FFT and order analysis.
5. Sound analysis shows increase in spund pressure level with increase in load, speed and defect of the gears.

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