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TOOLS AND TECHNIQUES

Early Detection of Failure of Spiral Bevel Gears Used in Differential Gearbox

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Abstract Spiral bevel gears are critical machine components used in almost all automotive differential gear boxes and main rotor drive systems for rotorcrafts. In this paper, noise and vibration approach is described for condition monitoring of spiral bevel gears. A fatigue test rig is developed to test the differential gearbox of an automobile using NVH approach. Experimental tests are conducted on test spiral bevel crown wheel and pinion used in differential gear box to study the noise and vibration characteristics of the gears during operation and also to determine the fatigue life of given spiral bevel gears pair. The test gears are loaded with rated torque with a factor of safety of two, until the pinion fails. Correspondingly the data are logged to record the noise and vibration of the gear pair. The vibration and noise signals are acquired experimentally on time response, and then, these are plotted on frequency response for three different cases viz new gear pair, used gear pair and gear pair after breaking of one tooth of the crown pinion. By studying the characteristics of noise and vibration spectrum condition monitoring and fault diagnosis of the given differential gearbox is possible. By onboard measurement of noise and vibration, early detection of failure of spiral bevel gears pair during operation is accomplished.

Keywords Spiral bevel gears · Acoustic sensor · Accelerometer · Condition monitoring

Introduction

Gears are the main components of mechanical power transmission systems. Spiral bevel gears are critical machine components used in almost all automotive differential gear boxes and main rotor drive systems for rotorcrafts. Due to the demand for maximum power capacity, minimum weight and reliability, the fatigue strength of individual gear is significant. These gears are usually required to operate at extremely high fluctuation of speeds and loads and carry high power levels during such operating conditions. Hence, successful operation of geared system is very important for safety and reliability.

Failure of a gear during operation results not only in higher cost of replacement or repair but also the down time of the system. Hence, early detection of gear failure will play a significant role in saving these costs.

Spiral bevel gears have curved and sloped gear teeth in relation to the surface of the pitch cone resulting in formation of an oblique surface during gear mesh allowing contact to begin at one end of the tooth (toe) and smoothly progress to the other end of the tooth (heel) providing additional overlapping tooth action. Hence, the ability of spiral gears to change the direction of the mechanical load coupled with low noise and vibrations make them more suitable to use in automobile differential gear boxes.

Handschuh and Lewicki [1] carried out experimental endurance testing of four sets of prototypes of face gears of half the size, for feasibility of use in helicopter transmissions at 271 kW load at 19,100 rpm of the drive pinion. All

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four gear sets ran successfully at 100 percent of rated speed and torque for thirty million pinion cycles and further two gear sets ran thirty million pinion cycles at 200 percent of rated speed and torque. They measured and compared sound pressure levels and vibration levels at both pinion and crown wheel side during operation.

Lewicki et al. [2] tested experimentally an improved design spiral bevel gears for reduction in weight and noise and increase in life. Improvement in design were achieved by changing the material, modifying fillet radii to reduce stress due to tooth bending and tooth geometry modification to reduce noise by reducing torque transmission errors. Tooth deflection, noise and vibrations were measured and compared with original gears. A significant reduction in noise and stresses in gear material were achieved.

Akata et al. and Gasparini et al. [3, 5] carried out a bending fatigue test of single tooth by using a three-point bending load. It gives very rapid results compared to life tests which are very time consuming and expensive. Finite element analysis was carried out to determine stresses in spur gears.

Sureshkumar et al. [4] carried out failure analysis of bevel pinion and gear of gearboxes of an aero engine. By studying visual inspection, stereo-binocular, fractographic, microstructure, hardness and composition, they concluded that failure was due to multiple independent fatigue cracks.

Hohn et al. [6] observed that flank breakage is the most common mode of failure in bevel gears. Hence, they developed a theoretical method to calculate load capacity of bevel gears due to flank breakage and methods to avoid it with a sufficient factor of safety. By experimental tests, they found that flank breakage was not due to initiation of cracks from inclusions but due to endurance failure. The core hardness and case depth along with torque load were the decisive parameters for flank breakage.

Pavlov [7] has estimated rate of wear, efficiency and service life of straight bevel gears having orthogonal axis by theoretical computation considering the velocity of sliding and viscosity of lubricating oil.

Wirth et al. [8] evaluated the possibilities of failure of bevel and hypoid gears due to flank breakage or subsurface fatigue against the failure due to pitting, by using a proposed new calculation method. The validation of new method is shown with the help of experimental testing. A considerable number of bevel gear sets used in gear drives of axles in test vehicles failed due to flank breakage. Hence, the gears were redesigned using new design method with small material exposure so that both flank breakage and also to a greater extent reduction of pitting failure was achieved.

Wang and McFadden [9] described a system using image processing techniques for automatic detection of vibration signatures of gears for fault diagnosis and early detection of failure. They concluded that the short time frequency transform (STFT) as the most powerful tool for early detection of damage to gear.

Wang [10] used a resonance demodulation technique for detecting cracking of the gear teeth at early stages. The residual signals were generated by removing the harmonics of gear meshing by using a technique of synchronous signal averaging.

Mosher et al. [11] showed a detailed vibration signal analysis by carrying out destructive test of a spiral bevel pinion and gear pair. They examined the vibration signal in the frequency and time domains and four time-frequency transforms of gear vibration signals viz. the continuous wavelet transform (CWT), the short time frequency transform (STFT), the discrete wavelet transform (DWT) and the Wigner-Ville distribution with the Choi-Williams kernel (WV-CW). A study of all transforms revealed a change in the magnitude of vibrations of a new and damaged spiral bevel pinion.

Sar and Kumar [12], Jayaswal et al. [13] and Devendiran [14] have reviewed various researches on condition monitoring and detecting fault in a machine by using vibration signature analysis techniques. Vibration analysis techniques for diagnosing fault in various machine elements like gears, shafts, bearings, pumps, motors and beams are discussed.

Patil et al. [15] and Barshikar [16] have studied the vibration spectrums from a single-stage gearbox, occurring due to faulty gears and fluctuation in loads. They have setup a FFT analyzer to obtain the signals from gearbox loaded with the help of a rope-brake dynamometer. The study was carried out by creating various defects viz., one corner, two corner and three corner defects and a missing tooth. Barshikar [17] has tried to diagnose the fault in the gearbox by using motor current signature analysis (MCSA).

Analysis and testing of spiral bevel gears is an emerging research area. Limited work has been published on the estimation of fatigue life and the early detection of failure in straight tooth bevel gears. In addition, even more scarce is research for spiral bevel gears other than those for the parallel axis gears, which may be due to the very complex shape and special test equipment necessary to test these gears which makes it very difficult for study and consequently arrival at the proper conclusions. Failure of a gear during operation results not only in higher cost of replacement or repair but also the down time of the system. Early detection of the failure of a gear will play a significant role in saving these costs. Hence, there is a demand for the development of methodologies that incorporate the transformation of existing technology with suitable modifications. The main objectives of the present work are:

1. To design and develop a fatigue test rig for testing spiral bevel gears used in differential gear box using NVH (Noise Vibration and Harshness) approach, which can apply rotational dynamic loading as compared to the present test methods in which fatigue loading is applied on a single gear tooth.
2. To study the mechanism of failure of spiral bevel gears used in a differential gearbox under fatigue loading using the NVH approach, thereby facilitating early detection of failure of spiral bevel gears pair by condition monitoring.

Experimental Setup

A fatigue test rig was developed and fabricated to test the differential gearbox of a TATA Ace HT mini truck vehicle at Research Centre-Dept of Mechanical Engineering, Basaveshwar Engineering College, Bagalkot as shown in Fig. 2. Figure 1 shows the layout of the experimental setup. It consists of a three-phase AC 75 HP, 1500 rpm electric motor, which supplies rotational torque to the drive pinion (test gear) via a universal coupling. The crown wheel which is in mesh with the drive pinion is connected to an electric dynamometer via another universal coupling. Two accelerometers are used to sense the vibrations. One accelerometer is located on the main bearings of crown pinion (drive side) on the housing of the differential gearbox and another accelerometer is located on the crown wheel bearing (crown side) [6] as shown in Fig. 2.

An acoustic sensor (industrial microphone) was placed inline and one meter from the meshing of the two gears viz. crown pinion and crown wheel. Two tachometers (proximity sensor type) were used, one to measure the speed of the pinion shaft and the other to measure the speed of the crown wheel shaft. A four-channel data acquisition system with acquisition rate of 25600 samples per second was used to acquire the data from all the sensors continuously. As the magnitude of thermal stresses in the spiral bevel gears was very negligible compared to tooth bending stresses due to fatigue loading [1], the thermal effects were not considered in the present study. Figure 3 shows the drive pinion to be tested.

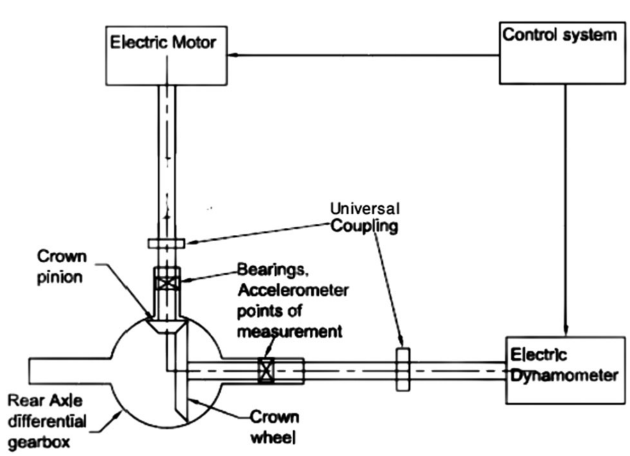


Figure 1 Layout of experimental setup

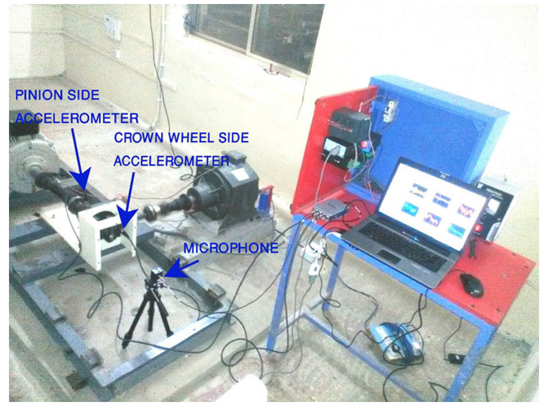


Figure 2 Position of sensors and data logger

Figure 3 Test spiral bevel crown pinion from differential gear box

Noise and Vibration Signature Analysis

The characteristic vibration pattern a machine generates during its operation is called the vibration signature of that machine. The actual vibration signal obtained from a transducer can be treated as the signature, but the vibration spectrum is usually called a signature. Vibration analysis starts with acquiring the accurate vibration signal from a vibration transducer usually an accelerometer. The analog signal converted to digital signal can be used for further processing and analysis.

The noise and vibration measurement test setup is shown in Fig. 2. A gradual break in procedure, as given below, was adopted on the first build of the test rig due to uncertain capabilities of the spiral bevel gear assembly. The test spiral bevel gears are run initially at low torque and speed for about 30 minutes for stabilization. The test rig is shut down and the gears are inspected visually. After the inspection, the torque and/or speed was increased. The same procedure was repeated for all the break-in

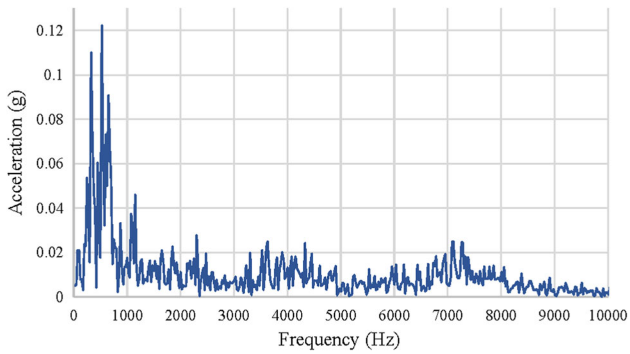


Figure 4 Vibration spectrum of crown pinion in frequency domain for new gear pair

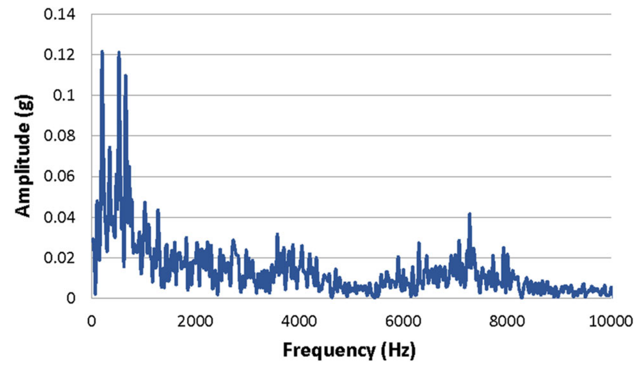


Figure 5 Vibration spectrum of crown pinion in frequency domain for the used gear pair

conditions. The data are logged by a DAQ (Data Acquisition System) which was connected to a Laptop PC.

As the maximum rated torque for the given differential gearbox is 37.5 Nm, hence 200 percent of the rated torque, i.e., 75 Nm was applied on the drive pinion at 1500rpm. The procedure adopted to log the signals is as discussed below; the analog signals from accelerometer and microphone are logged as discrete time data (raw data). Then these data in the time domain are converted into frequency domain to plot the vibration and noise frequency spectrum of crown wheel and pinion.

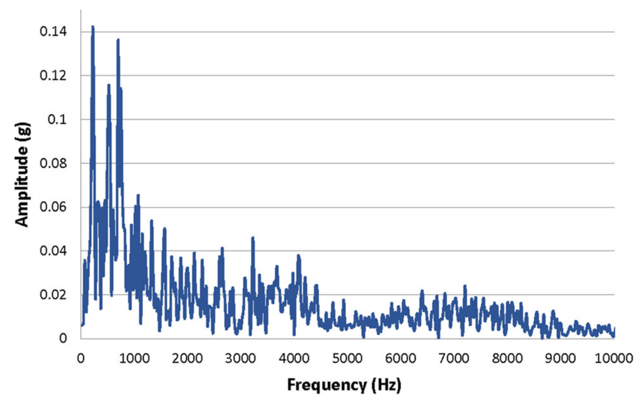


Figure 6 Vibration spectrum of crown pinion in frequency domain for the damaged gear pair

Results and Discussion

The measurements were taken in three stages viz:

1. For the new crown pinion and wheel pair
2. For the crown pinion and wheel pair after running for about 3.2 million pinion cycles, which is referred to as used gear pair and
3. For the crown pinion and wheel pair after breaking of one tooth of the pinion, this is referred as damaged gear pair.

The plots of vibration acceleration measurements in time domain are converted into frequency domain using a FFT and are shown in Figs. 4, 5 and 6.

From the vibration spectrum on pinion side for new gears pair from Figure 4, it can be observed that the peak accelerations are concentrated between o and 1000 Hz, whereas for used gears from Fig. 5 it can be observed that the peak accelerations are concentrated between 0 and 800 Hz, and that for damaged gears from Fig. 6 it can be observed that the peak accelerations are concentrated between 0 and 800 Hz.

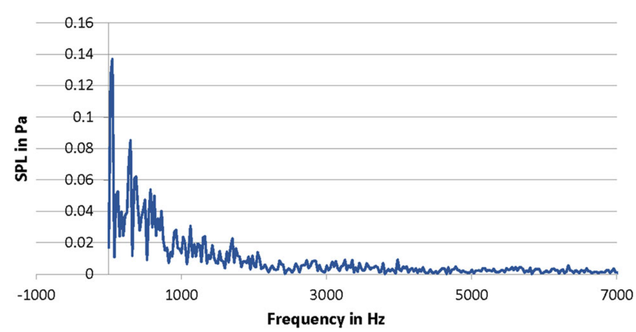


Figure 7 Sound pressure level for the new gear pair in frequency domain

A calibrated unidirectional industrial microphone is used to sense the transverse noise of the differential gearbox which includes both the gear meshing and mechanical noise with some spatial disturbances. The sensor is positioned in the straight transverse direction to the meshing spiral bevel gears. The acquired data are used to determine the steady-state noise levels in dB to indicate gears meshing noise at a speed of 1500 rpm of the drive pinion.

The plots of sound pressure measurements in time domain are converted into frequency domain using a FFT and are shown in Figs. 7, 8 and 9.

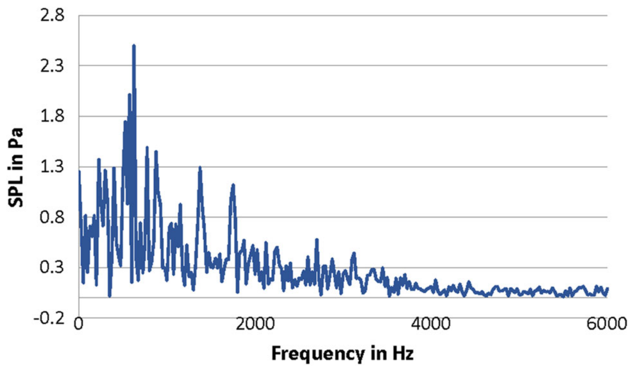


Figure 8 SPL for the used gear pair in frequency domain

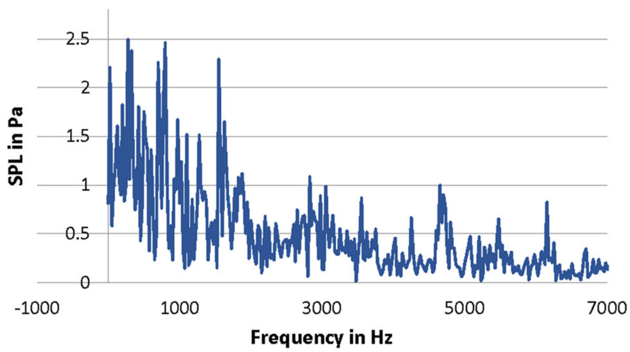


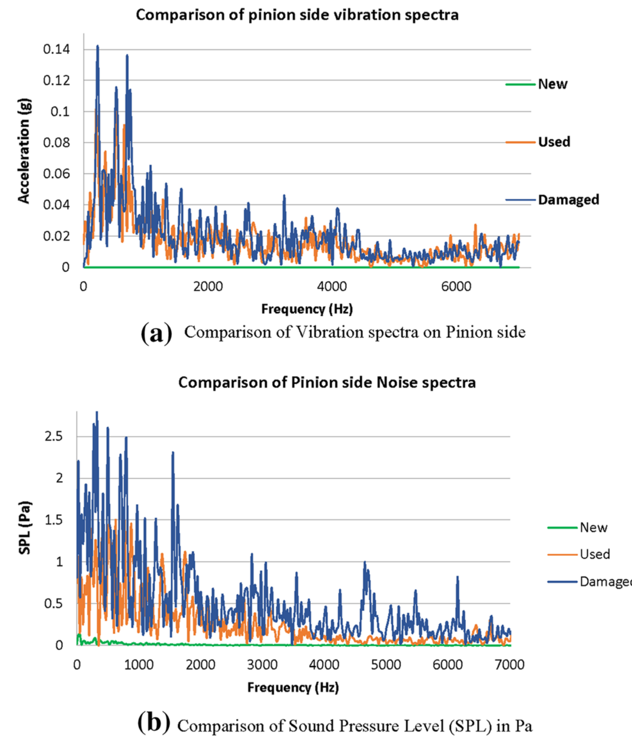
Figure 9 SPL for the damaged gear pair in frequency domain

Comparative Spectrum Analysis

The vibration and noise spectrum in frequency domain of the new, used and damaged gear pairs are compared with each other in Fig. 10. The vibration spectrum and noise spectrum from Fig. 10 show that there is a significant increase in noise and vibration level for the used crown wheel and pinion pair and a further increase in noise and vibration levels for the gear pair with a broken tooth of the pinion gear, as compared to the new pair of crown wheel and pinion. Hence, by investigating the noise and vibration spectrum which yields the noise and vibration signature, it is possible to know the condition of the crown wheel and pinion pair and a peak rise in noise and vibrations level are observed just prior to failure.

Pitting on the surface of gear tooth was observed after 3.2 million pinion cycles, which is due to surface fatigue. At 9.2 million pinion cycles, there is failure of one gear tooth of the pinion gear resulting in peak rise in vibration and sound level.

Hence from Figs 9 and 10, it is evident that the noise and vibration spectrum for new, used and damaged gear pairs vary significantly. Hence, by onboard measurement of noise and vibrations, it is possible for early detection of failure of the spiral bevel gear pair used in differential gear box of automobiles.



(a) Comparison of Vibration spectra on Pinion side

(b) Comparison of Sound Pressure Level (SPL) in Pa

Figure 10 Comparison of vibration and noise spectra

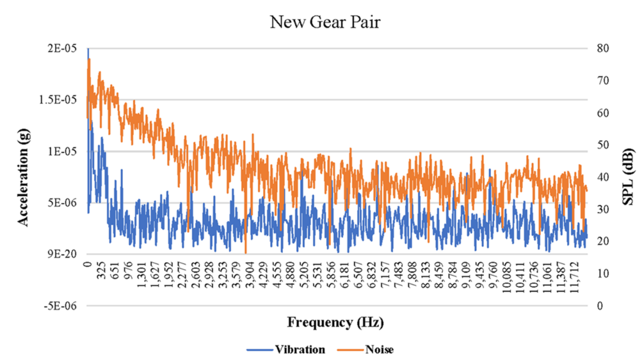


Figure 11 Comparison of noise and vibration spectrum on drive side.

Figure 11 shows the comparison of noise and vibration spectrum on drive side. The study of vibration and noise spectrum of spiral bevel gears pair depicts that noise amplitude and the vibration amplitude are having similar trends and are proportional. However, for a damaged gear pair, the noise level remained high for all frequencies which shows that there is a deterioration of the material properties viz., stiffness and elasticity.

Conclusions

The aim of this work, as noted earlier, is to experimentally develop a methodology to determine the fatigue life of spiral bevel gears used in automobile differential

Table 1 Specifications of test spiral bevel gears used in differential gearbox

Description	Pinion	Crown wheel
Number of teeth	8	39
Material	EN19/AISI 4140/42CrMo4	EN19/AISI 4140/42CrMo4

gearboxes. The results obtained from experimental measurement of noise and vibrations can be used to determine the condition of the test spiral bevel gear pairs in dynamic conditions of operation. The given crown wheel and pinion pair showed surface pitting due to surface fatigue after 3.2 million pinion cycles and there was failure of one tooth of the pinion at 9.2 million pinion cycles.

Due to the additional overlapping of gear teeth in case of spiral bevel gears, the gear pair performed well even after the breakage of one tooth of the pinion but resulted in a steep rise in the noise and vibration levels. The noise and vibrations measured are very low for a new set of gears and increased considerably for used gear pairs and there was a very steep rise in noise and vibration level for the damaged gear pair. By studying the noise and vibration spectrum (vibration signature) condition monitoring and fault diagnosis of the given differential gearbox is possible and by on-board measurement of noise and vibration early detection of failure of spiral bevel gear pairs during operation was accomplished (Table 1).

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