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Experimental Setup and Methodology to Carryout Fatigue Testing of Spiral Bevel Gears Used in Differential Gear Box Using NVH Approach

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Abstract. Currently the fatigue testing of bevel gears are being done by using non rotating type of fixtures that applies fatigue load on a single tooth, which does not resemble the actual loading condition in an automotive differential gear box. This paper discusses the experimental setup with the noise and vibration analysis approach to determine the signature of failures of spiral bevel gears. The proposed experimental setup seems promising for further research and development in the fatigue testing of spiral bevel gears.

The Crown pinion and wheel assembly is used for the testing. The pinion is connected to the electric 3 phase AC motor of 75HP with a suitable coupling and the crown wheel is mounted on the half axle shaft, which in turn is connected to an electric dynamometer. The speed/torque of electric motor and the load applied by the dynamometer can be varied. The acoustic sensor is mounted near the differential gear box and the accelerometers are mounted on the Pinion bearing, Crown wheel bearing and the half axle bearing.

A four channel data acquisition system is used to log data in time domain (raw data) by three accelerometers and an acoustic sensor. The variations of sound pressure(dB) v/s time, sound Pressure(FFT-(RMS)) amplitude v/s Frequency, Acceleration v/s Time, Octave analysis i.e., Band power v/s Frequency, Noise spectrum Power v/s Frequency, Histogram, Power density v/s Time can be obtained. These data are then used to plot vibration and SPP levels in frequency domain to develop the noise and vibration signature of that crown pinion for given cycles of operation. The tests on Bevel pinion and gear set were performed in the BEC, Bagalkot NVH lab facility. The gear set run successfully at double the rated torque for 30 million pinion cycles. And the signature of pinion failure was obtained. The results demonstrated the suitability of using the given bevel crown pinion and gears set for specified speed, high load application in differential gear box of an automobile.

Introduction

Spiral bevel gears are critical machine components used in almost all automotive *differential gear boxes* and main rotor drive systems for rotorcrafts. Demand for maximum power capacity, reliability and minimum weight are such that fatigue resistance of individual gear tooth is significant. These gears are typically required to operate at extremely high rotational speeds and carry high power levels for such operating conditions, successful operation of geared system is paramount to safety and reliability.

Analysis and testing of bevel gears has been an emerging area of research and sparsely any open literature is available as compared to that existing for parallel axis gears. This may be due to the complex gear geometry and specialized test equipment necessary to test these components and arrive at proper conclusions. Like all mechanical components, gears can and do fail in service for a variety of reasons. In most cases, expect for an increase in noise level and vibration, total gear failure is often the first and only indication of a problem. Many modes of gear failure have been indicated, like fatigue, impact, wear and plastic deformation. Among these failures one of the most common causes of gear failure is tooth bending fatigue. It results in progressive damage to gear teeth and ultimately leads to complete failure of the gear.

The design and manufacturing of low noise high endurance spiral bevel gears is carried out by application of local synthesis algorithm, tooth contact analysis and stress analysis by application of finite element method [1].Single tooth bending fatigue test of gear blank is carried out by using three point bending loading [2]. A single tooth bending (STB) test procedure has been developed to optimally map material, design and manufacturing parameters of helicopter case carburized gears [3]. A new material—physically based calculation method is used to evaluate the load capacity of bevel and hypoid gears [4]. A computational method is proposed for the predictive assessment of wear and service life of cylindrical gears [5]. A review of different modes and causes of failure of a bevel gear is presented in [6]. The design and development of a power re-circulating test rig for testing gear samples is proposed in [7].

Estimation of wear, service life and efficiency of the straight orthogonal bevel gear is achieved by a computational method [8]. An integrated computerized approach is proposed for design and stress analysis of spiral bevel gears [9]. Drive line analysis is used for tooth contact optimization of high power spiral bevel gears [10]. A new methodology based on a general mathematical model of the generating process is proposed for tooth contact analysis of hypoid bevel gears [11]. A 3D finite element model of a theoretical assembling straight bevel gear pair is proposed to analyze the contact fatigue on the tooth surface and the bending fatigue in the tooth root [12]. A finite element numerical modeling of materials response in gears tooth root and life prediction considering crack initiation period is developed [13]. Current developments in gearbox dynamic modeling are reported, the influence of the clutch damping coefficient and one random parameter value from the three-parameter error mode, and the interaction between error parameters on the vibration generated by a gearbox system, is analyzed [14]. The boundary element method and linear elastic fracture mechanics theories are used to predict three dimensional fatigue crack trajectories in a spiral bevel pinion under a moving load. An approach that accounts for fatigue crack closure effects is developed to propagate the crack front under the non-proportional load. The predictions are compared to experimental results [15]. Nonlinear time-varying mesh characteristics are used for study of dynamics of hypoid gear transmission. The coupled translation-rotation vibratory response of hypoid geared rotor system due to loaded transmission error excitation is studied by employing a generalized 3-dimensional dynamic model [16].

Limited work has been recorded in the experimental prediction of fatigue life of spur and helical gears and very scarce work has been recorded for bevel gears which is clear from the literature survey.

Objective of the work.

The main objectives of the proposed work are:

1) To design and develop a Fatigue test rig for testing differential gear box which can apply rotational dynamic loading as compared to the present static loading test methods which use static fatigue loading. The experimental results obtained from the test can be analyzed to predict the fatigue life of spiral bevel gears.
2) To demonstrate the suitability of using the given bevel crown pinion and gears set for specified speed, high load application in differential gear box of an automobile.
3) To investigate key design parameters in accordance with industry standards and recommended practices for use in an automotive differential gear box.

Layout of experimental setup.

Fig. 1 shows the description of layout of all the equipments in the proposed experimental setup, Fig. 2 and Fig. 3 shows the actual test rig developed in the research center i.e., Basaveshwar Engineering College, Bagalkot,Karnataka, India, for fatigue testing of spiral bevel gears used in the differential gear box of an automobile.

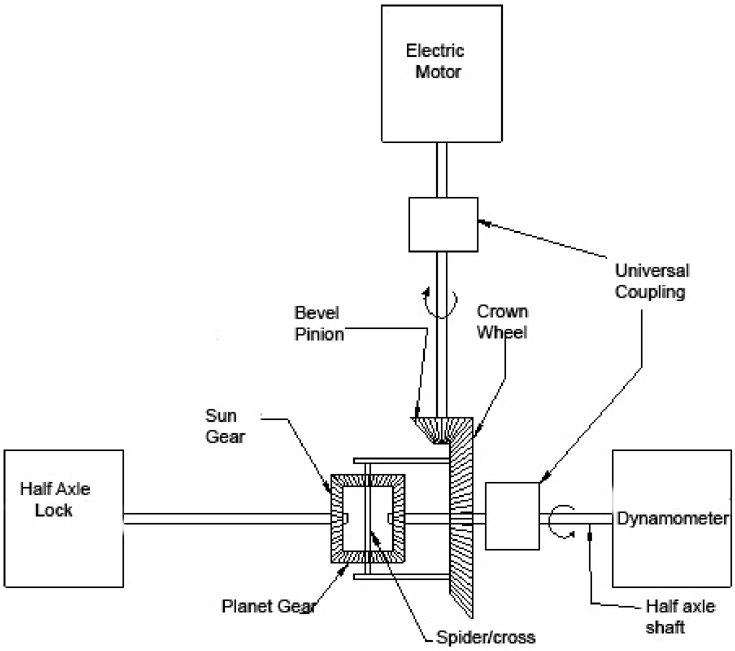

Fig.1 Layout of Proposed Experimental setup.

Fig.2 Test rig for fatigue testing of spiral bevel gears.

Fig.3 Test rig for fatigue testing of spiral bevel gears.

The Crown pinion and wheel pair to be tested is mounted in the differential gear box of the test rig. The pinion is connected to the electric 3 phase AC motor of 75HP with a suitable coupling and the crown wheel is mounted on the half axle shaft, which in turn is connected to an electric dynamometer. The speed/torque of electric motor and the load applied by the dynamometer can be varied. The acoustic sensors are mounted one near the pinion and other near the crown wheel and the accelerometers are mounted on the Pinion bearing and Crown wheel bearing.
A four channel data acquisition system is used to log data in time domain (raw data) by two accelerometers and two acoustic sensors. The variations of sound pressure(dB) v/s time, sound Pressure(FFT-(RMS)) amplitude v/s Frequency, Acceleration v/s Time, Octave analysis i.e., Band power v/s Frequency, Noise spectrum Power v/s Frequency, Histogram, Power density v/s Time can be obtained. These data are then used to plot vibration and SPP levels in frequency domain to develop the noise and vibration signature of that crown pinion for given cycles of operation.

Experimental Procedure.

Following are the specifications of the gear pair tested. The maximum test torque was selected based on the rated torque of the given vehicle's differential gear box (150Nm @1500rpm)

Table 1 Dimension of Test Drive Pinion and Crown Wheel.

Sl No.	Dimensions	Drive pinion	Crown wheel
1	Pitch cone diameter [mm]	41	180.5
2	Number of teeth	8	43
3	Module [mm]	6	5
4	Pitch angle [deg]	10.53	79.46
5	Normal depth of addendum [mm]	6	5
6	Normal depth of dedendum [mm]	6.94	5.78
7	Normal addendum angle (deg)	11.11	9.26
8	Normal dedendum angle (deg)	12.86	10.71
9	Whole depth of tooth (mm)	12.94	10.78
10	Pressure angle	25^0	

Results.

Performance test at Maximum rated torque (150Nm):
The test rig was run for 30 million pinion cycles after which both the pinion and crown wheel showed minimal surface change from their original with small areas of micro pitting scattered randomly over the root surface of the contacting teeth profile. The pinion teeth had more surface changes than gear wheel.

Performance test at Double the Maximum rated torque:
After successful completion of test at Rated torque, the torque was increased in the increments of 30Nm for every 1 hour of operation until 300Nm torque was reached. The test rig was again run for 30 million pinion cycles. Both the pinion and gear tooth surface showed moderate wear and random micro-pitting. Pinion showed more wear and deeper pitting compared to gear. At 300Nm torque the test was run again. At about 9 million pinion cycles the failure of the pinion was observed with accompanied little high noise and vibration and the test was terminated.

Table 2 Testing conditions.

Tests	Million Pinion cycles	Pinion speed		Torque on Pinion	
		rpm	% of Rated	Nm	% of Rated
Break in	5	360	25	37.5	25
		720	50	75	50
		1080	75	112.5	75
At max rated torque	25	1440	100	150	100
Up to double the Maximum rated torque	10	1440	100	187.5	125
		1440	100	225	150
		1440	100	262.5	175
At double the Maximum rated torque	20	1440	100	300	200
	9	1440	100	300	200

Table 3 Peak Sound Pressure Level (SPL) Measurement.

Pinion Speed [rpm]	Pinion Torque [N-m]	Pinion side SPL [dB]	Crown wheel side SPL [dB]
360	37.5	90	90
720	75	98	98
1080	112.5	105	106
1440	150	118	119
1440	187.5	118	118
1440	225	118	118
1440	262.5	118	119
1440	300	118	118
(At failure) 1440	300	135	136

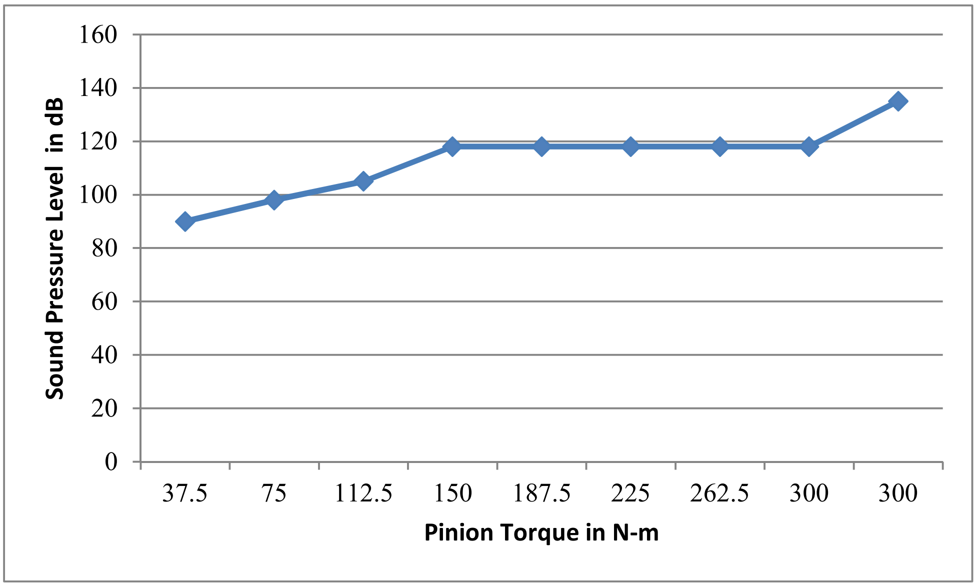

Fig.4 Sound Pressure Level measurement.

Conclusion.

In this paper a bevel gear test rig is designed and developed using noise and vibration approach to determine the signature of failures of spiral bevel gears used in differential gear box of an automobile. It resembles the actual loading condition in an automotive differential gear box. The given bevel crown pinion and wheel of Mahindra jeep was tested and the signature of the pinion failure is obtained for the test cycles performed. After running for about 30 million cycles at double the rated torque, the failure of the pinion tooth was observed at about 9 million pinion cycles with a increased noise level of 136dB.

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