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Appendix

Experimental test rigs and measurement instrumentation

A.1 Introduction

Two experimental test rigs where developed to determine the influence of fluctuating load conditions on structural response measurements. Spur gears and helical gears were considered in the test rigs. Different levels of gear damage were induced onto the gears of the rigs in order to generate measurement data under different loading conditions, to validate the signal processing procedures presented in chapters 2, 3 and 4.

A.2 Load control

The load on the gearbox test rigs were applied with a 5.5 kVA Mecc alte spa three-phase alternator. An analogue controller was designed to manipulate the electromagnetic field strength in the alternator in order to change the load, which was applied to the system. Figure A.1 shows a schematic diagram of the loading system.

The Alternating Current generated by the alternator is rectified and dissipated over a large resistive load, which is kept constant during tests. A single-phase voltage feedback from the alternator is measured in order to give an indication of the current, which is drawn from the alternator since the resistance was kept constant. The current drawn from the alternator is related to the torque applied by the alternator onto the system. Hence, the voltage feedback serves as an indication of the torque applied by the alternator.

A reference or command torque signal is used as an input to the controller, which manipulates the electromagnetic field strength in the alternator by switching the current flow to the DC field coils of the alternator with a transistor in order to follow the command signal. An external Direct Current (DC) power supply is utilised to provide the power for the DC field coils of the alternator. The controller utilises Proportional Integral (PI) compensation. Figure A.2 shows the load controller and DC rectification circuits. The resistive bank and external DC power supply is shown in figure A.3.

Note that the amplitude of load fluctuation decreases as the loading frequency or rate of load change increases due to the inertia and inductance in the system. The excitation frequencies during experiments were therefore kept below 3 Hz in order to obtain maximum load fluctuation amplitudes.

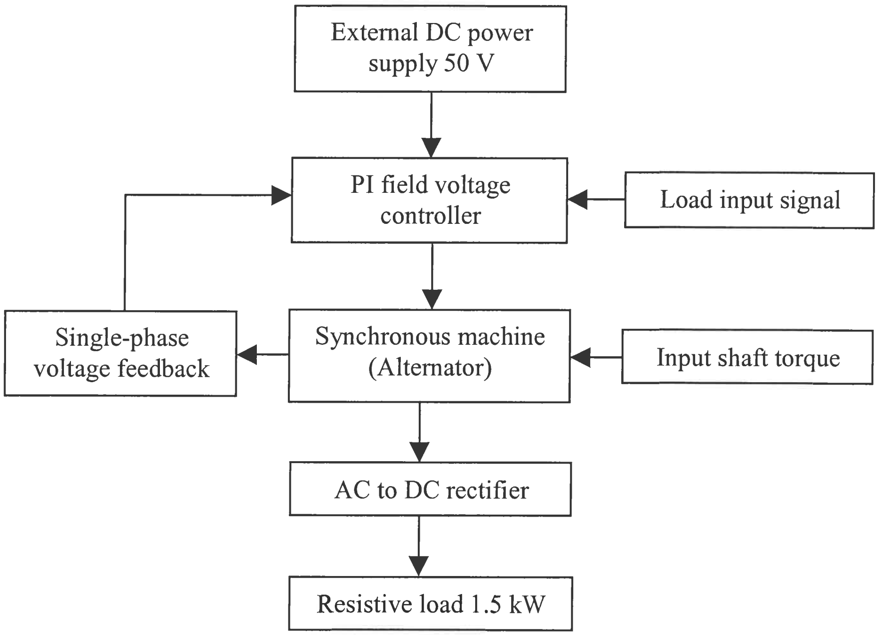

Figure A.1 Schematic diagram of the gearbox test rig loading system.

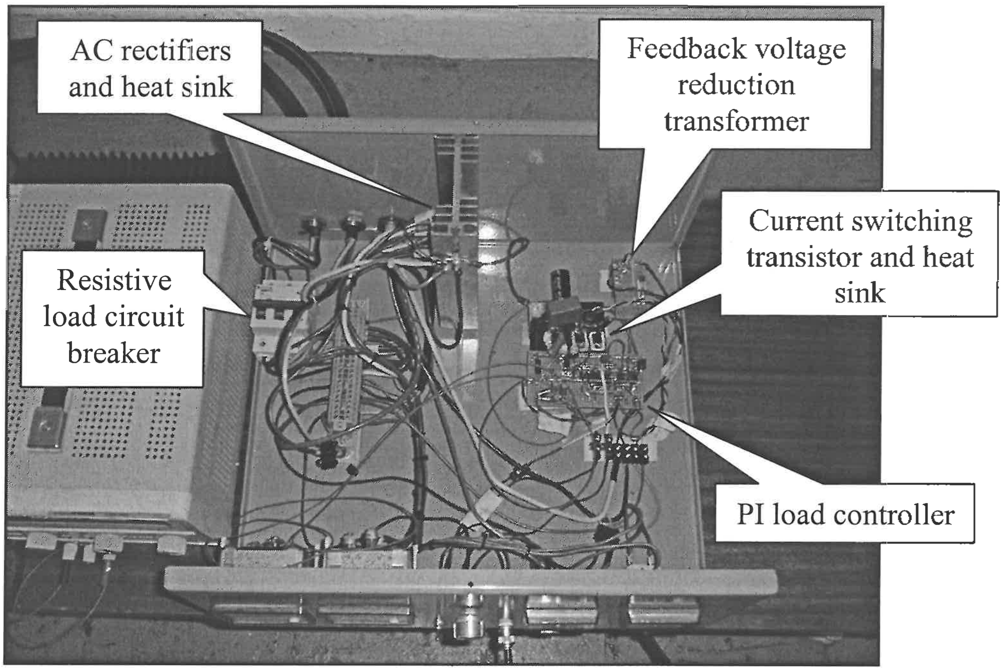

Figure A.2 Load controller electronic circuit

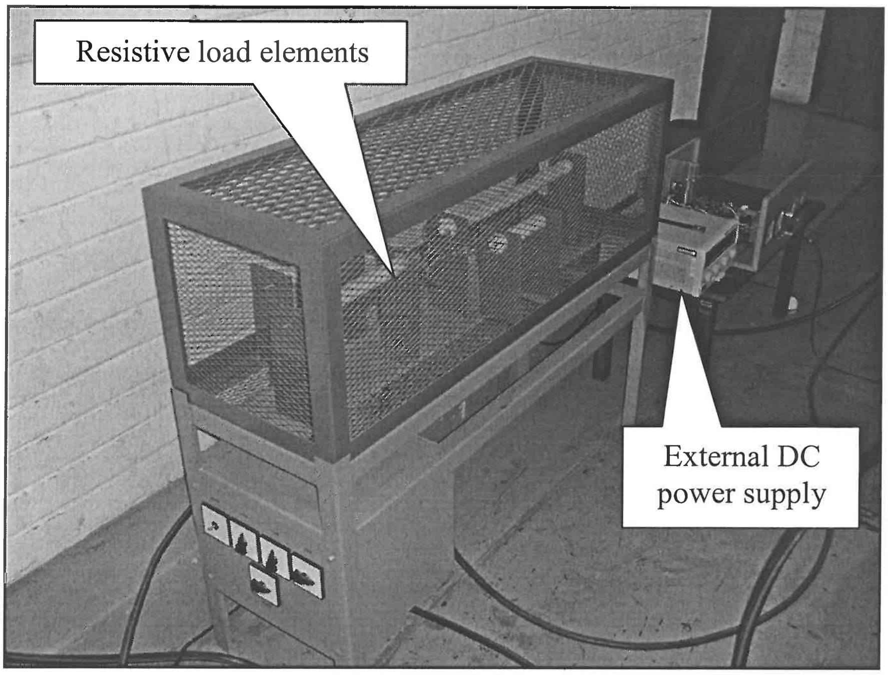

Figure A.3 Resistive load

A.3 Measurement system and instrumentation

The measurements were taken with a Siglab model 20-42 signal analyser and a Pentium 200 MMX Personal Computer (PC) with 64MB of Random Access Memory (RAM) shown in figure A.4. Four Analogue to Digital (A/D) channels where used to measure the key phasor, gearbox casing vibration, shaft speed and electric motor current signals. The virtual function generator was used to generate the load command signals for the load controlling system on the test rigs.

Integrated Circuit Piezo (ICP) accelerometers with a signal conditioner unit was utilised to measure the gearbox casing vibration. An accelerometer with higher sensitivity was utilised for measurements on the helical gearbox test rig due to the low amplitude response of the test gearbox casing vibration.

A magnetic speed sensor was user to measure the speed on the spur gear test rig. The shaft encoder was introduced in the helical gear test rig in order to improve the accuracy of the speed measurement from 50 pulses per revolution to 1024 pulses per revolution, which enabled the use of the IAS as a diagnostic measurement.

A schematic diagram of the measurement and load control system is shown in figure A.5. Table A.1 presents a table of the instrumentation with the specifications, which were used during experimentation on the two test rigs.

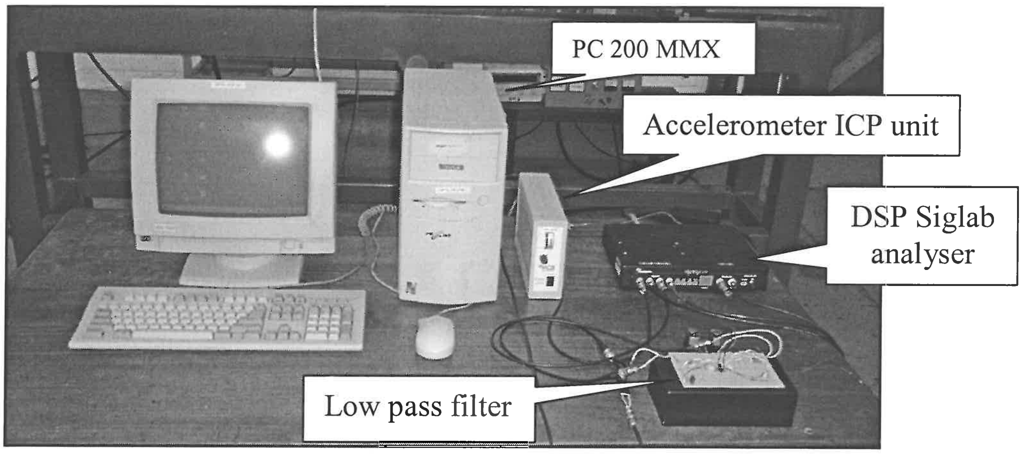

Figure A.4 Measurement system

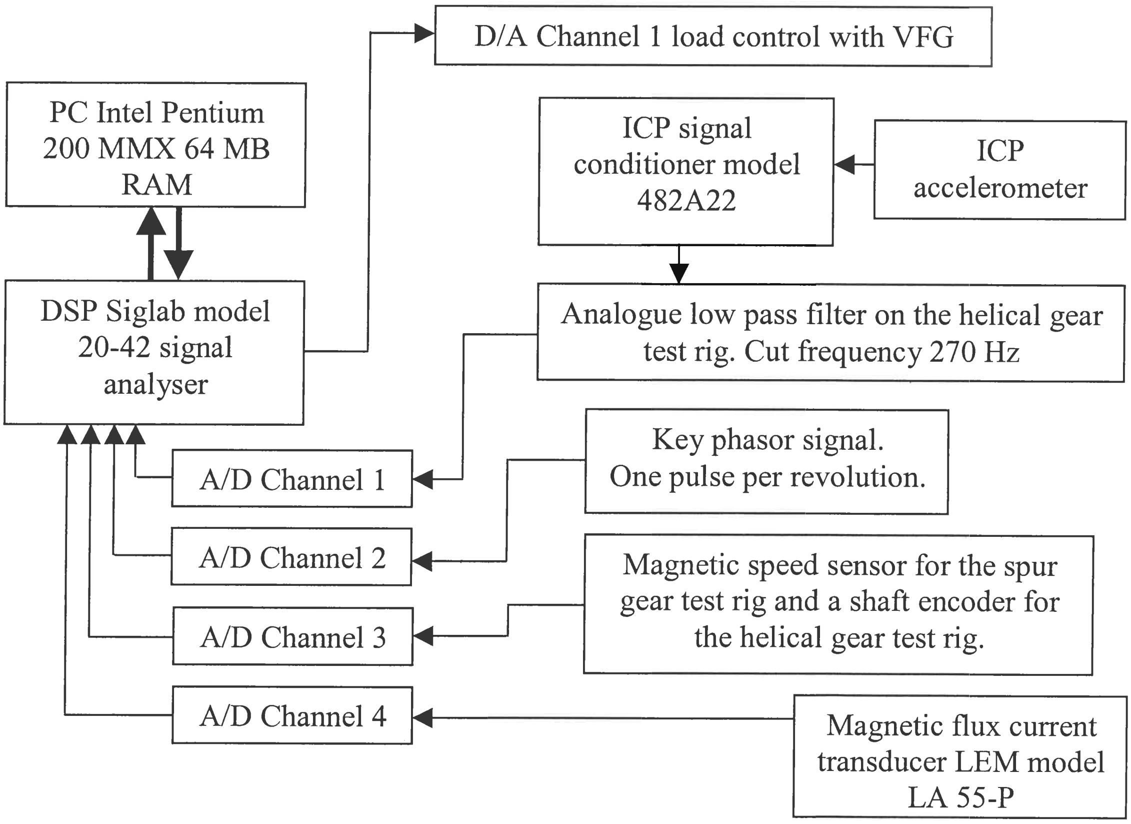

Figure A.5 Schematic diagram of the measurement and control system

Table A.1 Instrumentation

Instrument	Specification	Test rig
Signal analyser	DSP Siglab model 20-42	Helical & spur gear test rig
Personal Computer	Intel Pentium 200 MMX	
ICP Signal conditioner	PCB model 482A22	
Current transducer	LEM model LA 55-P	
Accelerometer 1	Entek 500 mV/g model E326A02	Spur gear test rig
Accelerometer 2	PCB 10 V/g model U393B12	Helical gear test rig
Magnetic speed sensor	Deuta-Werke model BM1/1A M14 × 1 × 50mm	Spur gear test rig
Shaft encoder	Hengstler model R176T01 1024ED 4A20KF	Helical gear test rig
Low pass filter	8^{th} Order Butterworth	Helical gear test rig

A.4 Low pass filter

The gear wheel of the test gearbox in the helical gear test rig is the slowest rotating component in the test rig with the lowest inertia which resulted in a relatively low gear mesh frequency amplitude when compared to the overall vibration levels. The anti-aliasing filter of the Siglab analyser has a constant cut off frequency of 20 kHz. An eighth order analogue Butterworth filter with a cut off frequency at 270 Hz was therefore designed and implemented as an analogue low pass filter. The high amplitude vibration in the frequency range above 270 Hz was therefore filtered out and the digitisation range of the gear mesh signal was improved.

The filter was designed with Microchip Filter Lab version 1.0.40. A frequency response function of the filter is shown in figure A.6. The schematic diagram of the filter with the component specifications is shown in figure A.7 and the physical hardware is shown in figure A.8. Two 9 Volt batteries was used to power the operational amplifiers of the active filter.

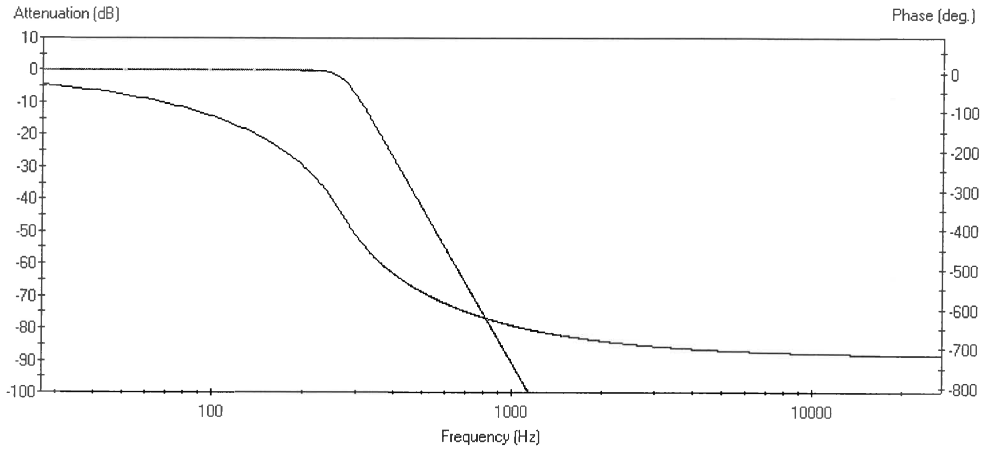

Figure A.6 Eighth-order Butterworth filter frequency response function

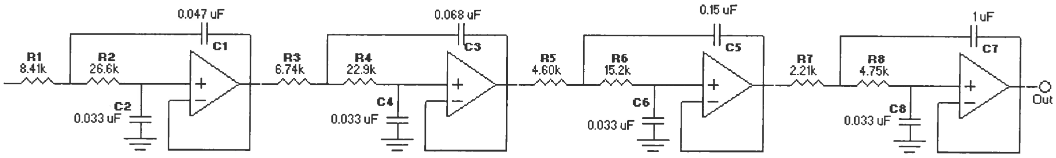

Figure A.7 Eighth-order Butterworth schematic diagram

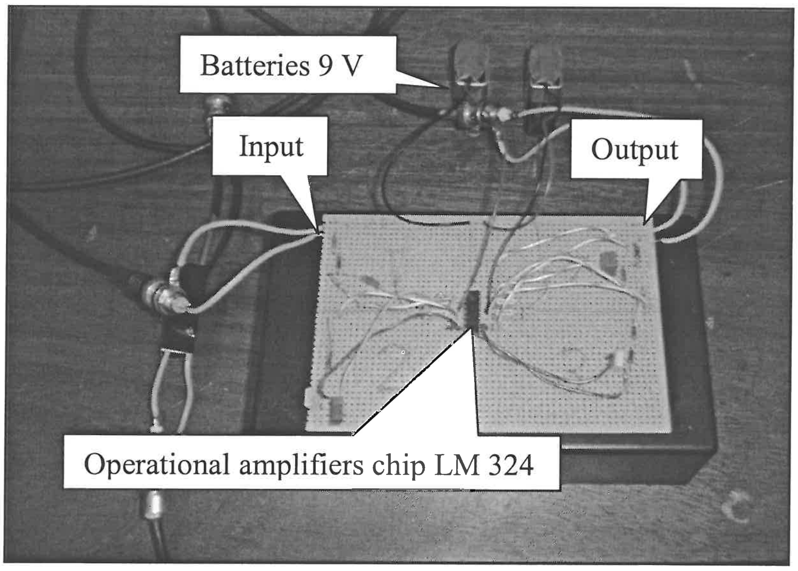

Figure A.8 Hardware implementation of the eighth-order Butterworth filter

The Butterworth filter phase distorts the measured data according to the frequency response function diagram shown in figure A.6. A reverse filtration scheme was developed to rectify the unwanted effect of phase distortion once the signals had been digitised. A random input filter signal was generated with the virtual function generator of the DSP Siglab in order to obtain input-output data from the analogue Butterworth filter, for the estimation of a system identification model. Measurements where taken with the DSP Siglab. An Auto Regressive model with eXternal input (ARX) was fitted on the data. A schematic diagram of the process is shown in figure A.9. The order of the measured data is reversed and re-filtered through the ARX model to remove the phase distortion. Once the data is re-filtered, the order of the data is reversed in order to restore the original sequence of the data. Only the phase of the data is effected by the reverse filtration procedure.

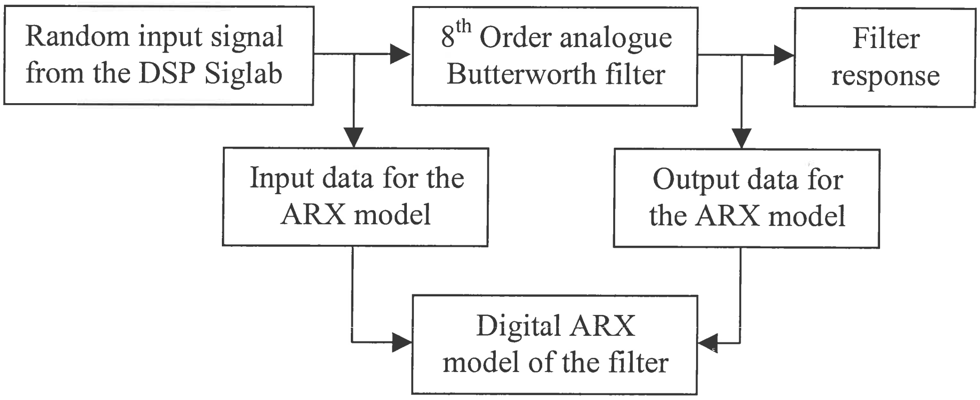

Figure A.9 Phase correction digital filter diagram

A.5 Spur gear test rig

The experimental set-up consisted of a single-stage gearbox, driven by a 5 hp Dodge silicon controlled rectifier motor. Load was applied with the system described in section A.2. The spur gear specifications are tabulated in Table A.2 and the test rig is illustrated in figure A.10.

Table A.2 Spur gear specifications.

Manufacturing standard	DIN3961, Quality 3
Number of teeth on each gear	69
Rated load	20 Nm

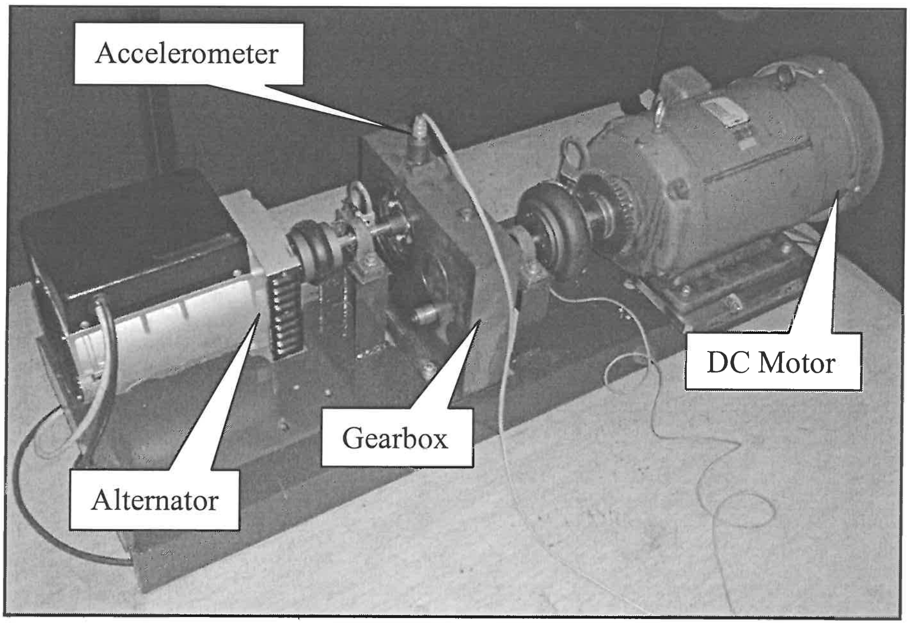

Figure A.10 Experimental set-up of the spur gear test rig

Tyre couplings were fitted between the electrical machines and the gearbox so that the backlash in the system would be restricted to the gears. The rotational speed of the system was measured with a Deuta-Werke magnetic speed sensor, which was set on a gear with 50 teeth as shown in figure A.11. The speed measurement gear was mounted on the output shaft of the electric motor. The magnetic speed sensor was utilised since it present a reliable and robust approach to speed measurement in practice. The average shaft speed during experimentation was 13 Hz.

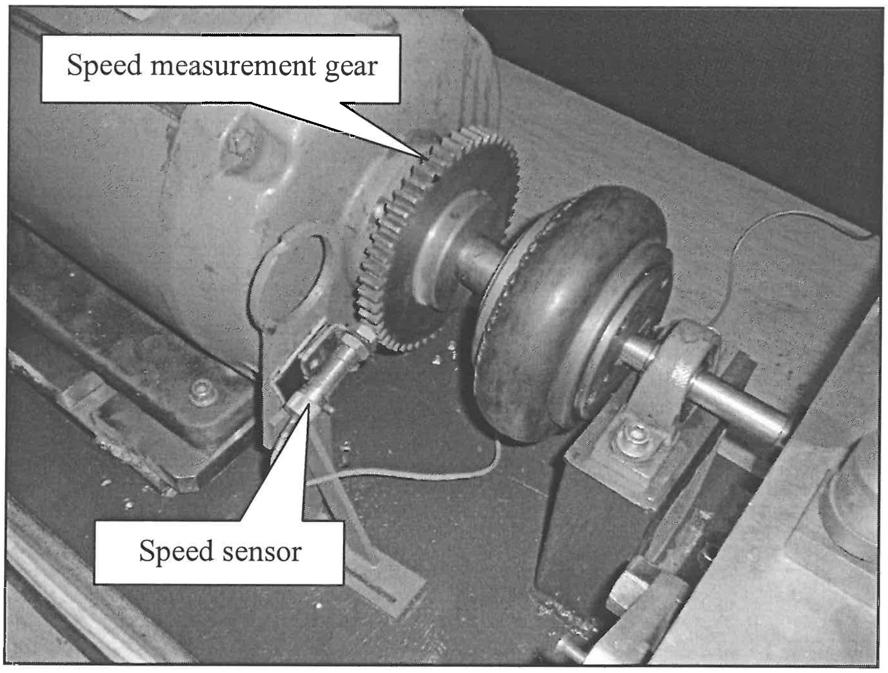

Figure A.11 Gear teeth counter in the spur gear experimental set-up

A synchronising pulse was measured by means of a proximity switch on the key of the shaft. Acceleration measurements were taken in the vertical direction with a 500 mV/g ENTEK ICP industrial accelerometer and the DSP Siglab analyser. Vibration measurements were taken for five different load conditions and three different levels of damage severity in order to evaluate the signal-processing procedures.

Table A.3 lists the specifications for the loading conditions. A sinusoidal load was selected to evaluate a slowly changing load condition, in contrast to the square load condition that creates a rapid change in load. The chirp load condition refers to a sinusoidal load condition where the frequency increases as time progresses. The chirp load condition represents a wider frequency band of the applied load.

The initial vibration measurements were taken without any induced damage. Then face wear was induced on one of the gear teeth by artificially removing material from the gear face. In addition, a crack was induced on the opposite side of the gear. Table A.4 presents the damage details and the induced damage is shown in figures A.12 and A.13.

The fault severity conditions are expressed as the fraction of the root crack length over the 4 mm tooth thickness.

Table A.3 Load case specifications

Load Case	Load Function	Frequency	Minimum Load	Maximum Load
1	Constant	0 Hz	14.4 Nm	14.4 Nm
2	Constant	0 Hz	15.9 Nm	15.9 Nm
3	Sine	0.5 Hz	6.6 Nm	18.6 Nm
4	Square	0.5 Hz	6.8 Nm	20.1 Nm
5	Chirp	0.1- 2 Hz	10.3 Nm	17.3 Nm

Table A.4 Induced damage specifications

	Fault severity 25%	Fault severity 50%
Material removed from face	0.15 mm Nominally	0.3 mm Nominally
Crack length	1 mm	2 mm

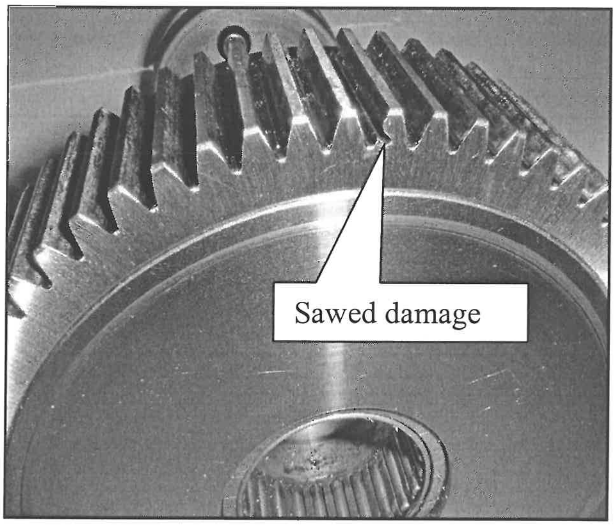

Figure A.12 Sawed crack

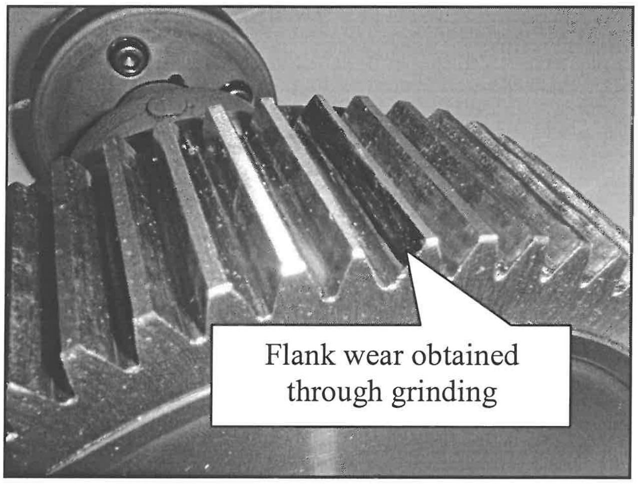

Figure A.13 Flank wear obtained through grinding

A.6 Helical gear test rig

The experimental set-up consisted of three Flender Himmel Motox helical gearboxes, driven by a 5.5 kW three phase four-pole Weg squirrel cage electrical motor. Load was applied with the system described in section A.2. Figures A.14 and A.15 illustrate the test rig. The gearbox test rig was designed to conduct accelerated gear life tests on the Flender E20A gearbox under varying load conditions. Two additional Flender E60A gearboxes were incorporated into the design in order to increase the torque that is applied to the small Flender E20A gearbox. The rated load of the gears in the Flender E20A gearbox was 20 Nm.

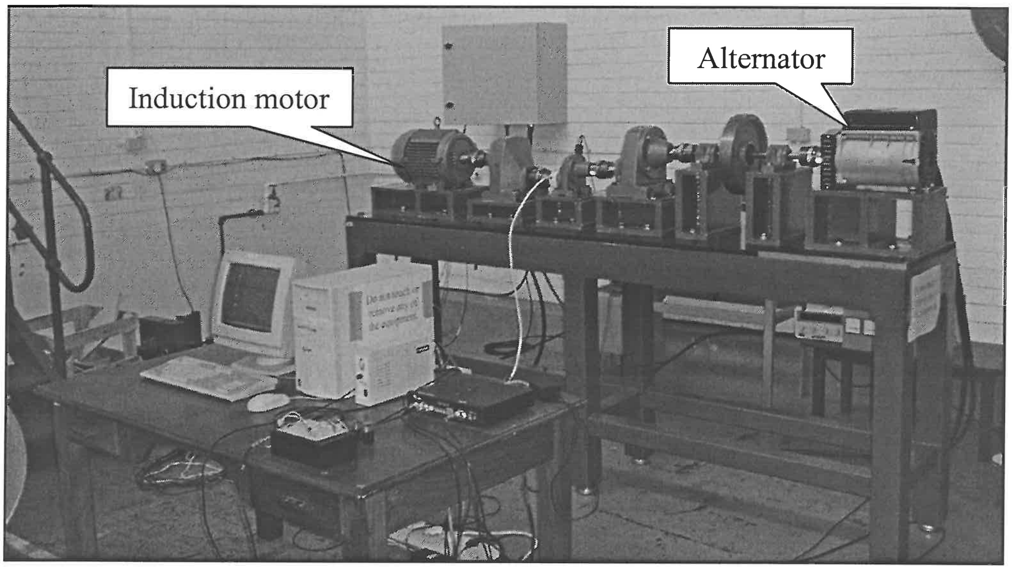

Figure A.14. Experimental set-up of the helical gear test rig

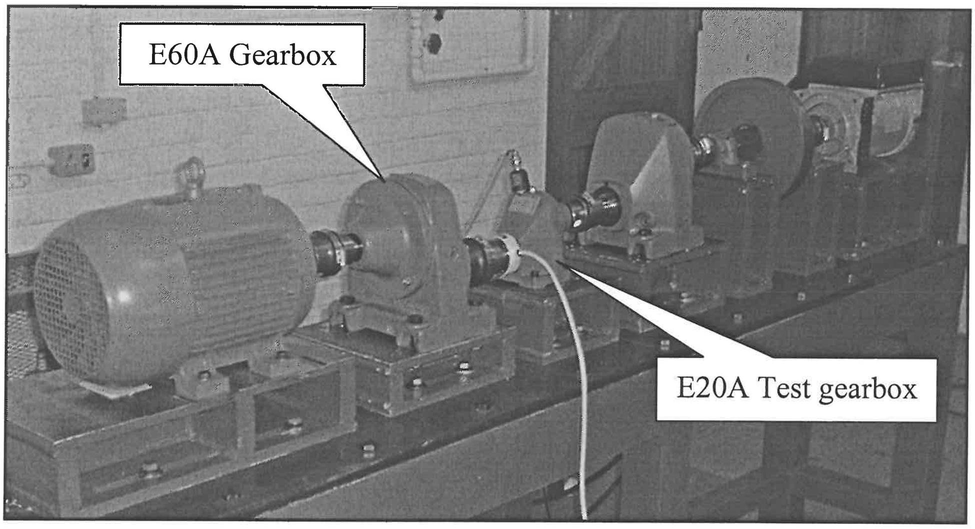

Figure A.15 Experimental set-up of the helical gear test rig

A Hengstler R176T01 1024ED 4A20KF shaft encoder, which produces 1024 pulses per revolution in the form of an analogue push-pull signal was used to measure the IAS for order tracking and condition monitoring purposes. The reference point for the synchronous averaging is measured as a single pulse from the shaft encoder.

Acceleration was measured in the vertical direction on the gear casing with a 10 V/g PCB ICP industrial accelerometer. The instrumentation is shown in figure A.16.

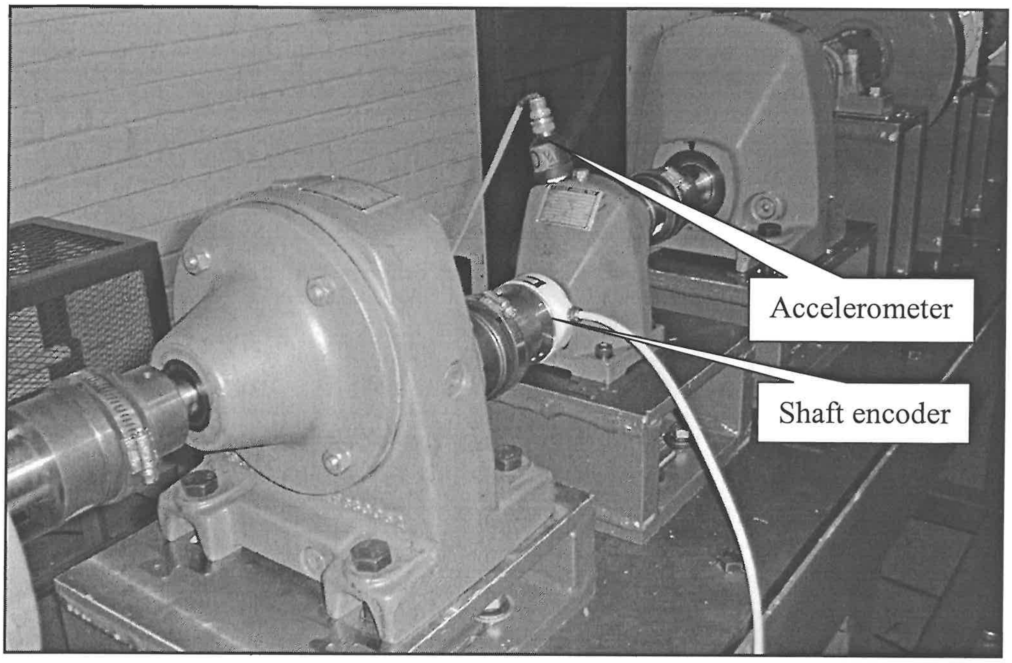

Figure A.16 Accelerometer and shaft encoder mounting positions

Reinforced concrete was cast into the base of the test rig in order to increase the damping levels in the supporting structure. This feature attenuated the response amplitude due to the transmission of reaction forces from the various rotating components. Concrete was cast into the supporting upright pillars in order to increase their stiffness as well as the damping levels. The mounting plate of the test rig was bolted on to the concrete in order to improve the damping effect. A base view of the test rig is shown in figure A.17.

Figure A.17 Concrete reinforcing of the test bench

A variable speed frequency drive shown in figure A.18 was incorporated to control the speed of the induction motor during start up since the initial start up torque produced by the motor will damage the gearwheel in the test gearbox. The rotational speed of the motor is increased from 0 to 25 Hz over a period of 30 s during start up.

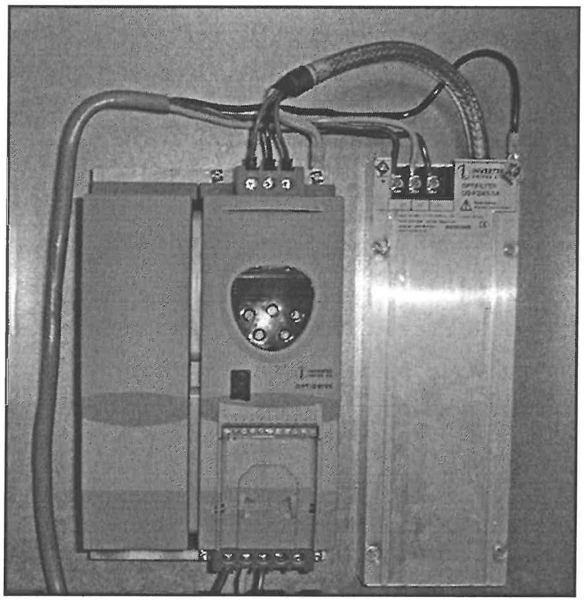

Figure A.18 Variable frequency speed control drive

The specifications for the loading conditions are tabulated in Table A.5. Flank wear was progressively induced on to one of the gear teeth on the gear wheel of the gearbox during experimentation. Details on the amount of wear are presented in Table A.6. The gearwheel of the test gearbox is shown in figure A.19.

Table A.5 Load case specifications

Load Case	Load Function	Frequency	Minimum Load	Maximum Load
1	Constant	0 Hz	10.7 Nm	10.7 Nm
2	Sine	1 Hz	7.4 Nm	14.7 Nm
3	Square	0.3 Hz	7.4 Nm	14.7 Nm
4	Chirp	0.1- 2 Hz	7.4 Nm	14.7 Nm
5	Random	0.1- 2 Hz	7.4 Nm	14.7 Nm

Table A.6 Induced damage specifications

Fault condition	Fault severity
1	100 μm Tooth face removal
2	200 μm Tooth face removal
3	300 μm Tooth face removal

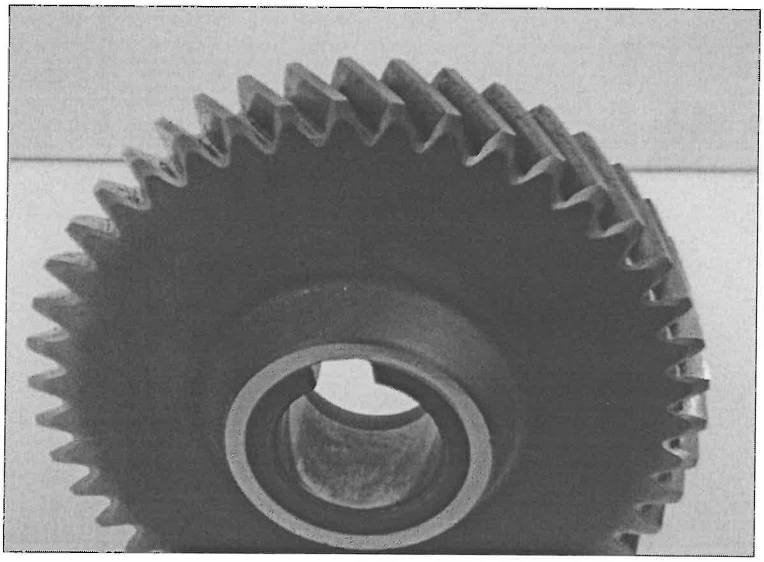

Figure A.19 Gearwheel of the E20A gearbox