Applied Mechanics and Materials Vols. 397-400 (2013) pp 176-188
Online available since 2013/Sep/03 at www.scientific.net

doi:10.4028/www.scientific.net/AMM.397-400.176

Design and Manufacture of a Planetary Gearbox Rig

A.O.Bligh[1,a] , N.A. Ahmed[1,a] and Y.Y.Zheng[1,2,c]

[1]School of Mechanical & Manufacturing Engineering, University of New South Wales, Sydney NSW 2052 Australia

[2]College of Aerospace and Materials Engineering
National University of Defence Technology, Changsha, China

[a]z9100160@unsw.edu.au; [b]n.ahmed@unsw.edu.au; [c]y.y.zheng@unsw.edu.au

Keywords: Planetary gear box, test rig, wind turbine, renewable energy; condition monitoring

Abstract: Planetary gearboxes are required in many applications but have a high failure rate especially in wind turbines where rapid growth in turbine size is placing larger demands on the gearboxes. Current condition monitoring techniques are less effective at detecting faults in planetary gearboxes due to the complexity of the internal rotating components. A small scale planetary gearbox was, therefore, needed for testing on a gearbox test rig to develop a more effective method of condition monitoring. The detailed computer design and manufacture of the planetary gearbox for this purpose is detailed in this paper.

INTRODUCTION

In the push for renewable energy sources [1-9], wind power is becoming one of the key technologies to which governments and energy companies are turning to reduce carbon output. To compete with conventional energy sources such as coal or nuclear, wind energy must become less expensive and more dependable. Improving the reliability of wind turbines is critical to both these objectives. One of the main contributors to turbine downtime is main gearbox failure [10]. Improving gearbox reliability is therefore a key performance goal for turbine manufactures and operators [11]. The aerodynamic research team of the University of New South Wales which has been heavily involved in the renewable energy studies [12-14], developing various passive [15-24] passive [25-42] flow control methodologies and diagnostics tools [43-58] started exploring new concepts to improve the fault diagnostic method of these gears. The present paper was formulated with such objectives in mind and to develop an effective vibration based condition monitoring system.

Vibration based condition monitoring (VBCM) is an effective method for improving reliability and predicting failures of machinery. The concept behind VBCM is to measure the vibration caused by moving components in a machine and then compare the signals to previous data or to a known standard. Significant variation of the vibration spectrum from base levels can indicate a fault or increased wear. The specific nature, location, and time until complete failure can be obtained from analysing the vibration spectrum closely. This information can be used to plan preventative maintenance, reduce downtime of machines and improve machine design.

Planetary gearboxes, such as those used in wind turbine gearboxes, are particularly difficult to monitor using traditional vibration analysis techniques [11]. This is partly due to their complex structure and large number of moving components. It is also due to the fact that the rotating planet gears are themselves mounted to the rotating planet carrier, creating a mechanism where the source of vibration is moving relative to accelerometers mounted on the casing of the gearbox. This causes the accelerometer to receive a modulated vibration signal from each of the planet gears thus making signal processing very difficult.

To overcome this difficulty, accelerometers have been mounted on the planet carrier itself. This gives vibration information from the same frame of reference as the planet gears and bearings and removes difficulties encountered with externally mounted accelerometers.

The aim of the project was to design and manufacture a planetary gearbox rig, test the rig with a number of different faults and capture data from accelerometers mounted in various locations.

DESIGN AND MANUFACTURE

The UNSW gearbox test rig was originally set up to operate with two gears on parallel shafts. This project involved the design of a planetary gearbox that could be accommodated into the rig with only minor modifications. The modified gearbox was designed to transfer power from the drive shaft though a set of spur gears to the planetary gear stage and thence to the driven shaft. This layout is similar to that used in modern wind turbine gearboxes.

The planetary gearbox test rig had to meet a number of requirements to be useful for vibration testing. These design goals were developed before the design process began and were updated throughout the design phase as the concepts for the gearbox rig developed.

Planet Carrier Mounted Accelerometer

A main objective of this project was to assess the fault detection performance of an internally mounted accelerometer against the typical accelerometer location used in condition monitoring systems. To achieve this, the gearbox had to be designed to accommodate a planet carrier mounted accelerometer.

A location and method for mounting the accelerometer onto the revolving planet carrier had to be developed as well as a method for transmitting the signal to the PULSE front end.

Maximum Torque

To ensure the most accurate simulation of an industrial planetary gearbox, it was important that the gear teeth mesh correctly. To facilitate this, the gearbox needed to have the maximum practical torque applied. It was therefore decided to install heat treated ground steel gears in locations with the highest torque loads such as the planet gears.

Easy Assembly/Disassembly

The gearbox also had to have easily removable and fully replaceable components as they would need to be changed regularly to test a number of different faults. This aspect of the gearbox is critical when the rig is used for gear fault testing. It is ideal to track the development of gear faults over time which requires the planet gears to be disassembled regularly.

Gear Ratio Selection

As the UNSW gearbox rig worked on the principals of a recirculating hydraulic system the gear ratio of the planetary gearbox had to be similar to that of the standard spur gears used (1:1). If the gear ratio of the total systems was too far from 1:1 the re-circulating hydraulic system could be damaged through a lack of adequate circulation.

Grease Lubrication System

The gearbox rig is typically run using oil lubrication. This allows the gears to be run at high torque loads by providing excellent lubrication and head dissipation properties. Oil lubrication also allows the rig to be run with some misalignment and incorrect centre distances (as required for Sweeny's testing) which can create a significant amount of sliding in the mesh.
For previous experiments the accelerometers used to measure vibration on the rig were placed on the outside of the gearbox housing. This separated them from the lubricating oil inside the gearbox, which is ideal as oil can damage the sensitive electrical connections on the accelerometers. As a planet carrier mounted accelerometer and slip ring were required for internal measurement, using oil lubrication was not possible. Oil inside the gearbox housing could have penetrated the seals on

the slip ring and affected the electrical contacts between the brushes and rings. This would at best alter the received signal and at worst damage the slip ring beyond repair.
To avoid these issues grease lubrication was used in place of oil. Grease does not provide as much lubrication or heat dissipation as oil but will not damage the delicate electronic equipment inside the housing. This restricts the maximum run time for the test rig as continuous operation would cause excess wear and overheating and frequent regreasing would be required.

Ease of Manufacture
As all the components for the gearbox would be fabricated by the UNSW workshop staff it was essential that the planetary system be designed for minimal machining time. This would ensure all the components could be manufactured quickly to allow time for testing and any modifications required.

Planetary Gearbox Concept
For the initial concept design it was crucial to find the correct combination of gears for the primary and secondary stages of the gearbox. This required considering the possible shaft centre distance allowed by the adjustability of the rig, as well as the largest ring gear that would fit inside the gearbox housing. The final gear ratio is also very important because of the hydraulic drive system used to load the gears during operation.

The concept developed around the used of an 80 tooth ring gear, three, 20 tooth planetary gears and a 40 tooth sun gear to give the planetary stage a gear ratio of 1:3. The planet carrier was connected directly to a large spur gear of 90 teeth, which meshed with a pinion gear of 32 teeth, mounted on the parallel. This allowed the two stages to transmit power from one shaft to another with a final gear ratio of 1:1.0667.

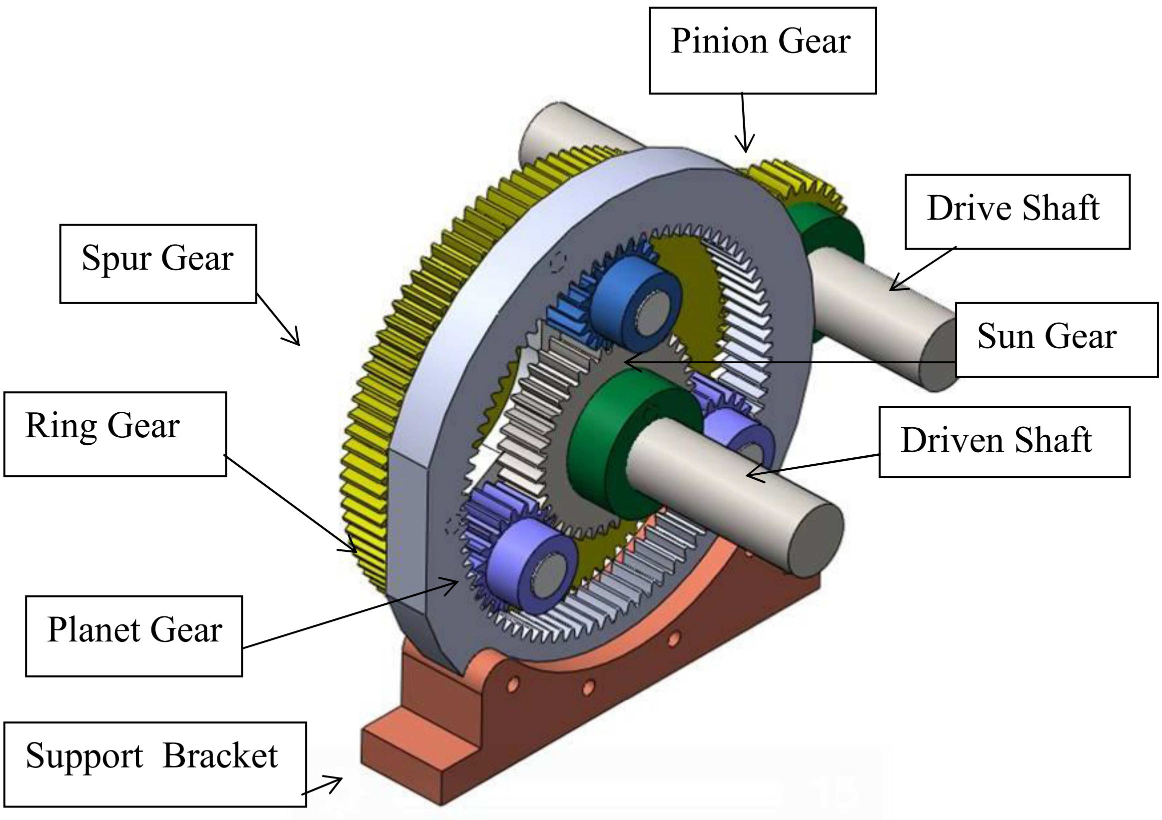

Fig.1: Initial planetary gearbox concept

Fig. 1 shows a CAD model of the preliminary design of the gearbox. The ring gear was initially to be supported by a bracket attached to the base of the gearbox housing. In the final design the supporting bracket was mounted on the top of the gearbox housing. This change was made as the base of the gearbox housing was not rigid enough to support the torque loads that would be applied to the ring gear during operation. The support bracket was also manufactured in two halves to reduce machining time.

Planetary Gearbox Detailed Design

The design of the gearbox focused on simplicity to allow for rapid fabrication and assembly. Each planet gear was held in place using a single M6 shoulder bolt, bolted onto the planet carrier. Each planet gear or bearing can be changed in five minutes allowing for frequent inspections. This makes the gearbox suitable for research purposes as components can be inspected or swapped frequently.

Planetary Gearbox Purchased Components

To reduce design time and cost, as many off-the-shelf parts as possible were used in the design. All gears were purchased from Ronson Gears Australia. Each gear required some modification to fit within the design. The modifications were carried out by the UNSW workshop to ensure accurate tolerances were achieved. Straight cut, ground, spur gears with a module of 2mm were chosen as they were hard enough to support the required loadings but could still be readily machined.

Table 1: Gear Load ratings and strength calculations

Gear	Rated Load (Nm)	Calculated Load (Nm)	Applied Load at 30 Nm nominal (Nm)
Pinion	45.2	T_{in}	30
Spur	222	2.815 x T_{in}	84.4
Planets	16.6	0.156 x T_{in}	4.7
Ring	57	0.625 x T_{in}	18.75
Sun	72.1	0.312 x T_{in}	9.36

Table 1 shows the rated loads of each type of gear provided by the manufacturer and the applied load relative to the input torque measured at the torque transducer; T_{in} represents Torque at meter. The applied torque calculations assume no losses due to friction. In practice the gears in the secondary planet stage will experience only 95% of the calculated torque load due to friction in the first stage.

Note that the torque calculated above does not show the total applied torque on each gear but the torque loading on an individual tooth during mesh. As such, each tooth on the sun gear and ring gear only experience 1/3 the torque applied to the entire gear as they are meshing with the three planets at any one time. The total torque applied to the sun gear is shown in the following equation:

$$3 \text{ x } (0.312 \text{ x } T_{in}) = 0.936 \text{ x } T_{in}$$

This fits with the calculated gear ratio of 1:1.0667 for a power efficiency of 100% assuming no losses is the system.

The bearings used in the gearbox were also critical to the design as they support the load of the gears. The existing gearbox rig already had two bearings, supporting each shaft in the casing. These bearings were large, double row, self-aligning ball bearings which allowed easy access the outer-race of the bearing by simply rotating the cage. This type of bearing is ideal as it can be disassembled and faults seeded on the inner and outer races or the rolling elements using an electrical discharge machine or a cutting tool.

Due to the small size of the planet gears, no standard size self-aligning bearings would fit within the design. Instead deep groove ball bearings were used. These could be obtained at the correct size for a reasonable price to allow for a number of different faults to be seeded. Deep groove ball bearings were also used for supporting the planet carrier on the driven-shaft. The calculated load on the planet bearings, at a torque load of 30 Nm, is only 234 N in ideal conditions. Under uneven load distribution the force could be as high as 460 N. This is well below the manufactures rated load of 1320N.

Planetary Gearbox Manufactured Components

The most critical part of the gearbox design and manufacture was the planet carrier shown in Fig. 2. This single part interfaces with almost every other component in the system and transmits torque from the first stage of the gearbox to the second. Another important function of the planet carrier was to align the planet gears axially and radially with the driven shaft while rotating independently of this shaft.

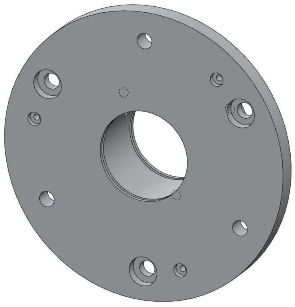

Fig. 2 Planet Carrier Design

The planet carrier transmitted torque from the spur gear to the planet gears and each planet gear was cantilevered off bearing pins. It was therefore essential that the carrier assembly was not only strong enough to support the applied loads but also stiff enough to allow only minimal deflections under load. Large deflections would cause misalignment between the planet gears and the ring gear causing increased vibration levels and tooth wear. The planet carrier was therefore analysed using Finite Element Analysis to ensure the required stiffness was achieved. The planet carrier was manufactured from 6061 Aluminium Alloy.

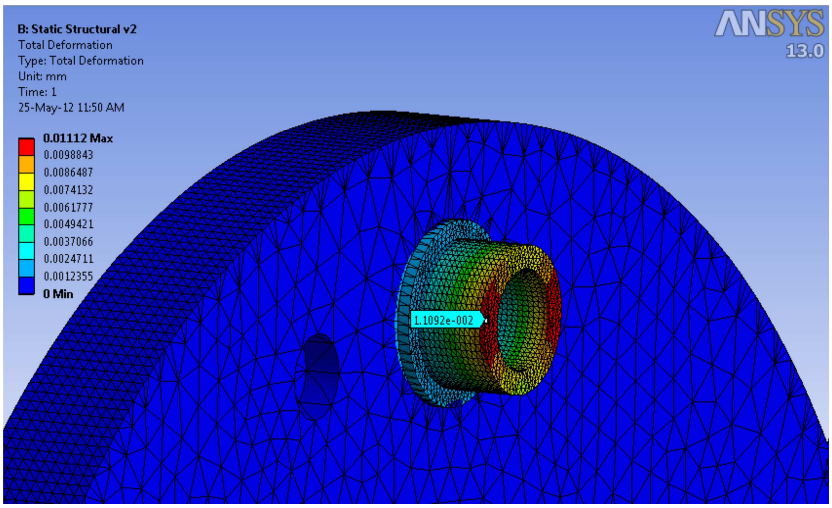

Fig. 3 Finite Element Analysis of the planet carrier

Fig. 4 shows the two main bearings which locate the planet carrier on the shaft and allow it to rotate independently. A shaft collar was used to mount the bearings on the driven shaft and locate the planet carrier axially. The collar also aligned the planetary stage with the driven shaft. Any misalignment in the collar or the main bearings would be amplified due to the diameter of the carrier and would cause a significant level of precession in the other components on the planetary stage.

The main carrier bearings fit over the collar and were held in place with two circlips. The collar assembly is shown in Fig. 4.

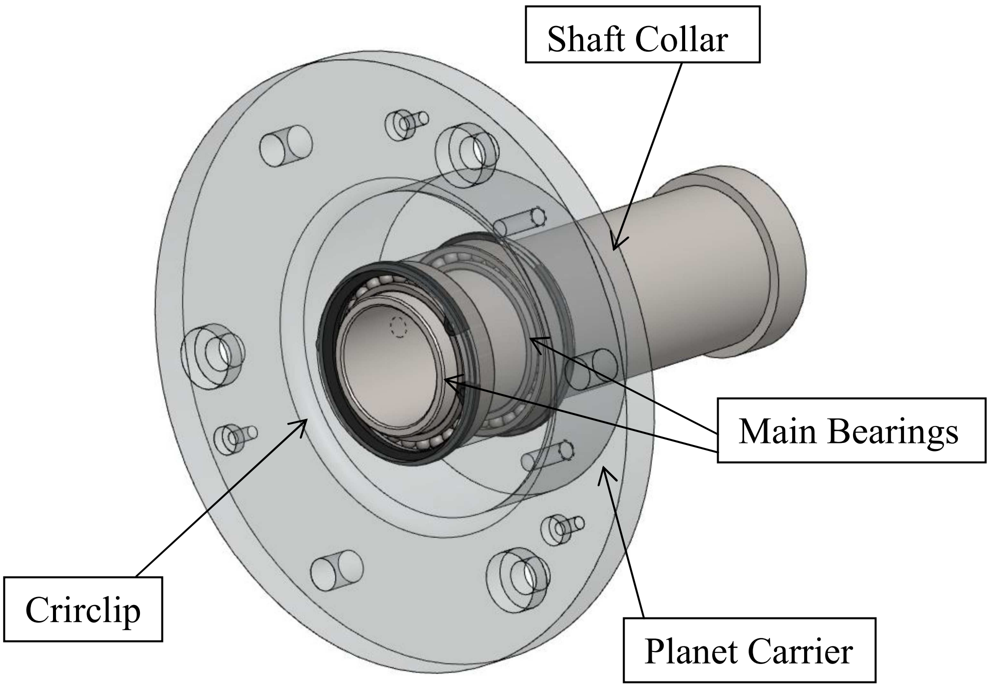

Fig. 4 Planet carrier with shaft collar and main bearings in position

The large spur gear was bolted to the carrier using three 8mm shoulder bolts. Shoulder bolts were used to ensure accurate location of the spur gear on to the carrier as any misalignment would affect its meshing with the pinion gear on the driving shaft.

Three steel pins were press fit into recesses in the carrier. One of the two planet bearings on each gear fits over this pin and inside the machined hole in the planet gear as shown in Fig. 5.

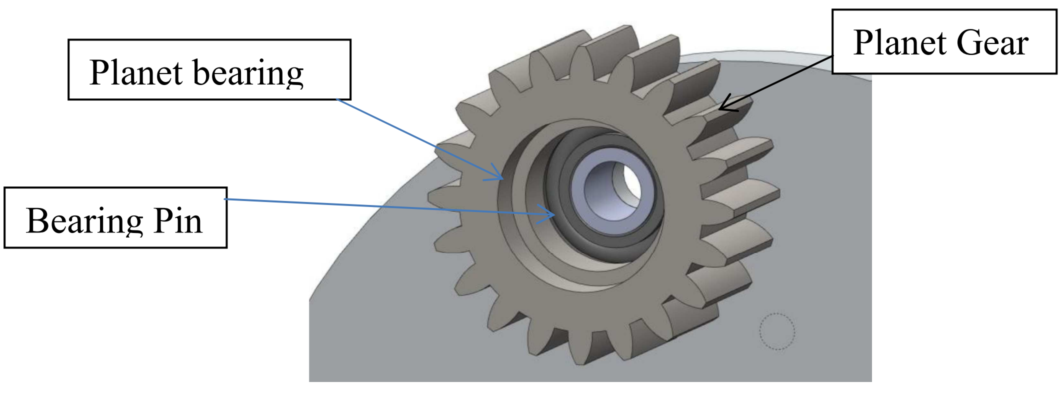

Fig. 5 Bearing Pin, Planet Bearing and Planet Gear

The other planet bearings fits into the opposite side of the planet gear with a steel bush located between the two bearings. The entire assembly is bolted together using an 8mm shoulder bolt. The accurately ground shoulder of the bolt fits tightly into the bearing bush, bearing pin and carrier ensuring that the planet gear is kept in the correct position relative to the Carrier.

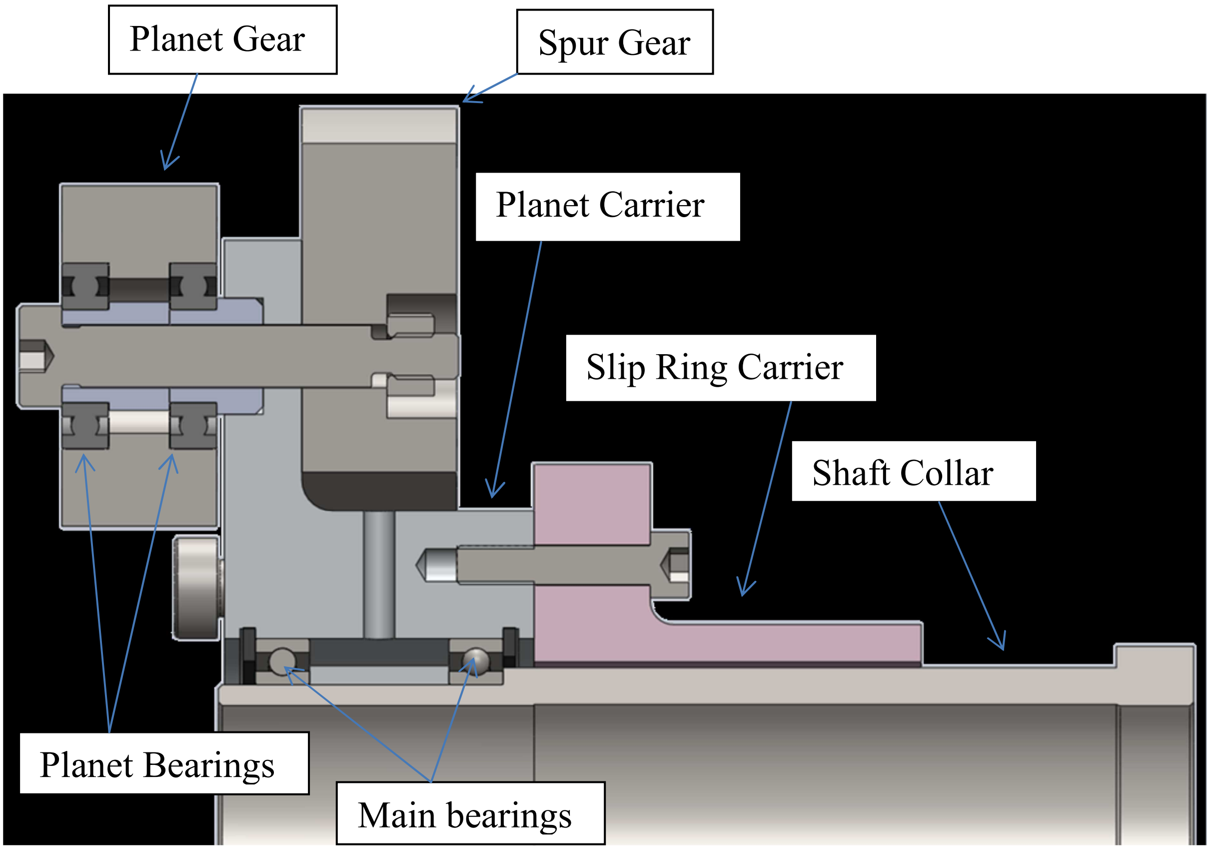

Fig. 6 Cross section of Planet Carrier Assembly

A cross section of the assembly is shown in Fig. 6. A small clearance on either side of each planet bearing allows some axial movement of the planet gear and reduces the sensitivity of the bearings to brinelling.

Fig. 7 shows a computer aided design (CAD) model of the final gearbox design.

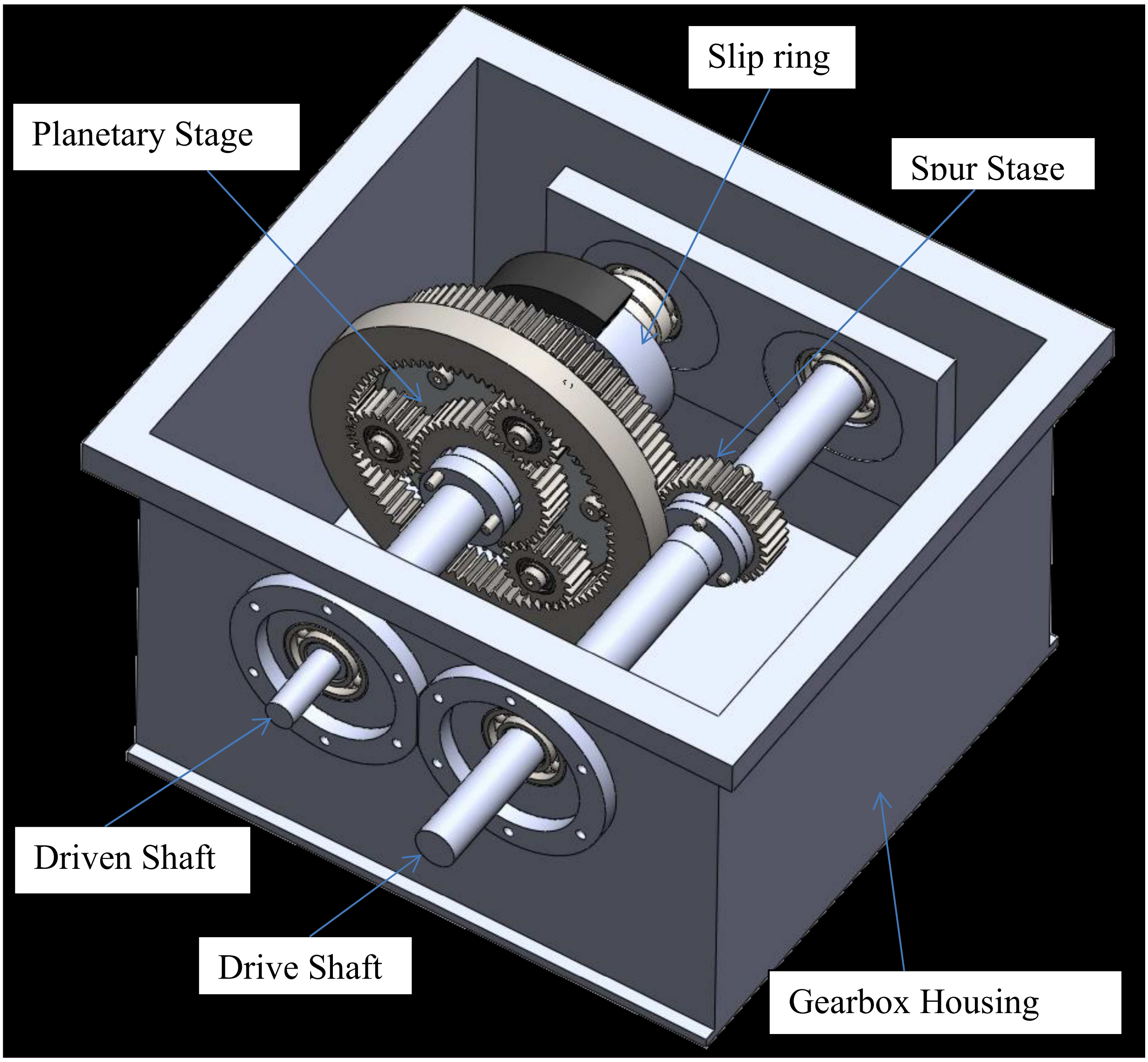

Fig. 7 CAD model of final Planetary Gearbox Design

ASSEMBLY

The assembly of the planetary gearbox was quite complex due to the large number of components within the planetary stage and the tight fits required on many components for smooth operation.

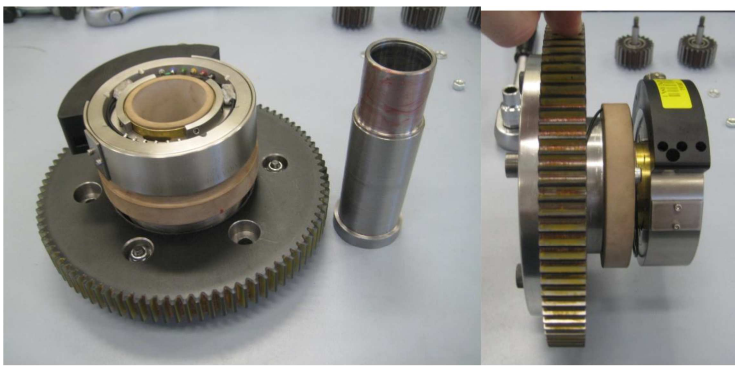

Fig. 8 Planet Carrier Assembly

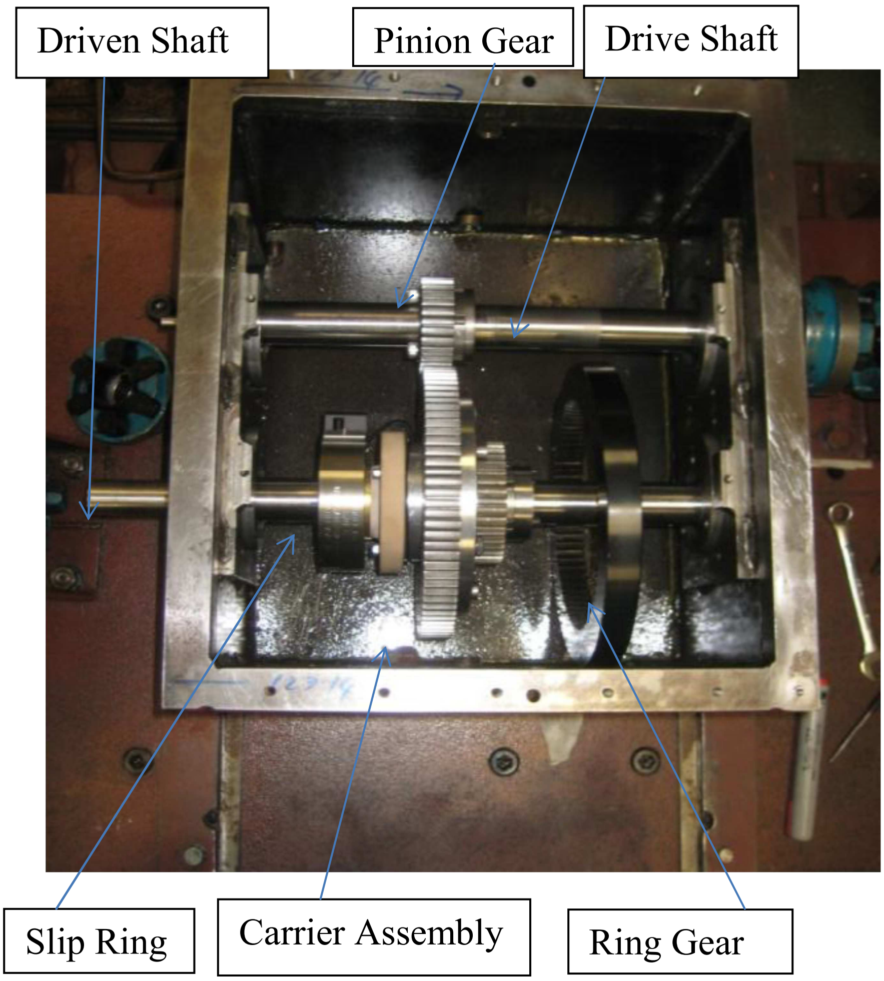

Fig. 9 University of New South Wales Planetary Gearbox during assembly

Most of the gearbox components can be assembled off the gearbox, fixed onto the driven shaft and then installed in the rig which reduces assembly time. The procedure is outlined below:

1. The first stage of the assembly process involves attaching the pinion gear and sun gear to the driving shaft and driven shaft respectively. They are located using the collars on the shaft and bolted to the shoulder using three M6 bolts.
2. The main bearings are then pressed into the planet carrier and locked in location with circlips. The accelerometer is then bolted onto the carrier before the large spur gear is accurately located in position on the carrier with the shoulder bolts. 3. The slip ring carrier is bolted onto the flange of the planet carrier and slip ring is then slid onto the carrier using six set screws to hold it in place. The assembly of the planet carrier with the spur gear and slip ring in place is shown in Fig. 8.
3. The shaft collar can then be pressed into the main bearings using the assembly tools. The shaft collar is then pressed onto the driven shaft leaving a 1 mm spacing between the carrier and the sun gear.
4. The driven shaft is then inserted into position in the gearbox housing with two bearings at each end of the shaft.
5. Fig. 9 shows both stages of the UNSW planetary gearbox inside the gearbox housing.
6. The planet gears are then bolted into place on the planet carrier. The shoulder bolts supporting the planet gears are then tightened in sequence to ensure the spur gear and the planet carrier are aligned correctly.

CONCLUSIONS

The planetary gearbox was successfully manufactured and fitted to the UNSW gearbox test rig and to the specialised rigs already designed and manufactured in relation to wind turbines [59-60]. Currently it is being used to develop a new approach to detect bearing fault. With accurate and consistent alignment of the gearbox components, the gearbox would be a useful tool for further research into condition monitoring [61]. This will further enhance the cause of better planetary gear design, fault detection and hence provide reliable and more effective maintenance procedures.

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