Main Gearbox Testing for Light Utility Helicopter of HAL

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Abstract
Non-destructive testing forms a very important part of development of systems during the design and development phase of a helicopter. Helicopter gearboxes are considered critical systems, as they transmit power from the engines to the rotors and accessories of the helicopter at the required speed and direction. The individual components of the gearboxes like gears, shafts, housings are subjected to various NDT techniques in HAL such as Magnetic particle inspection, X-ray and liquid penetrate checks. Final checks on the components include checking of all dimensions, surface finish, checking of special features such as splines, hardness checks, ensuring compliance to the specified manufacturing processes and finishing, prior to the subsequent release of acceptance tags for the accepted components.

While the above activities take care of the checks at the component level, checks at the assembly level are essential in order to ensure that the gearbox, as an assembly, meets the design requirements with regard to its performance under loads at the rated speed. The design and development of special test stands plays a crucial role in the assembly level testing of gearboxes. The tests are carried out at the development stage, wherein loads at the rated speeds are applied to check the proper functioning of the gearboxes, as well as in the prototype acceptance stage, wherein each gearbox identified for ground runs and prototype flight testing undergoes Non-destructive testing on the gearbox test stands. This paper presents the details of Main Gear Box tests performed for HAL’s Light Utility Helicopter on special test stands developed and commissioned at Ground Test Centre, RWR&DC, HAL.

Keywords: Main Gear Box, Closed Loop Torques, Mast loads, Test stands

1. Introduction

Power transmission from engine to rotors and accessories in helicopters is carried out by the Main Gearbox (MGB) via interconnecting shafts and gears. The MGB typically consists of the gearbox housing, gears and pinions, support bearings, freewheels, lubrication and cooling systems, accessory drive tap offs, monitoring sensors, and some of the components of rotor control mechanisms that are integral with gearboxes, such as swash plate mechanisms and control linkages [1].

![General schematic arrangement of gearboxes in a helicopter](https://example.com/image)

Figure 1 : General schematic arrangement of gearboxes in a helicopter
The MGB in a helicopter is designed based on:
- Engine Installation Features & Adequate Engine-to-Tail Drive Clearance
- Required power capability
- Suspension on Vibration Isolation System (VIS)
- Drive for Accessories
- Mounting of Main Rotor Actuators for Main rotor controls

The individual components of the gearboxes like gears, shafts, housings are subjected to various NDT techniques such as Magnetic particle inspection, X-ray and liquid penetrant checks. Final checks on the components include checking of all dimensions, surface finish, checking of special features such as splines, hardness checks, ensuring compliance to the specified manufacturing processes and finishing, prior to the subsequent release of acceptance tags for the accepted components. While these activities take care of the checks at the component level, checks at the assembly level are essential in order to ensure that the gearbox, as an assembly, meets the design requirements with regard to its performance under loads at the rated speed. Towards this, special tests were carried out on the MGB as follows.

2. Tests carried out on Main Gearbox of Light Utility Helicopter (LUH)

The LUH MGB has a single engine input, with outputs for main and tail rotor and accessories. Development and prototype Main Gear Boxes were designed and built by HAL for its LUH program, and tests carried were out as follows, for checking the conformance to design [3].

2.1 MGB Oil distribution checks

Oil distribution checks are necessary for checking the adequacy of the oil flow rates at the various gear meshes of the MGB. The Oil distribution checks set up comprised of an oil reservoir and an oil pump to feed the oil at the required flow rate to the MGB. The resulting oil pressure and flow at MGB inlet, TPTO (Tail Power Take-off) oil pressure, oil quantity collected from each jet, and the oil temperature were measured during the checks.

Figure 2 : Views of the MGB specimen with cut outs for Oil Distribution Checks
Apart from measurement of oil flow rates, the Oil Distribution Checks were carried out for determination of direction of oil jets and determination of pressure drop within the gearbox unit. The tests carried out were:

- Determination of oil flow rate at the outlet of each oil jet
- Determination of effect on oil flow rate and pressure by blocking of any one oil jet hole

Figure 3: Test Set-up for Oil Distribution Checks
The Oil Distribution Checks test set-up comprised of a Main tank filled with oil. The oil was fed to the inlet of MGB (at MGB filter) by using an external oil pump. The MGB was placed on an Auxiliary tank which was inter-connected with the Main tank. Photographs of test set-up are shown in figure 3. The oil was fed to the inlet of MGB, sprayed out from the MGB oil jets to the MGB internals, and got collected in the Auxiliary tank. This oil flowed back to the Main oil tank by gravity, thus completing the oil circuit. During the test, Oil Flow rate, MGB inlet pressure, MGB TPTO pressure, Oil temperature and ambient temperatures were measured. There were a total of over a dozen oil jets in the MGB. The oil used was JSD OX-38 oil as per DERD 2487. For the test, the external oil pump was switched on, and the flow rate was adjusted in steps as per the minimum flow rating of the MGB oil pump. After completion of the tests at minimum flow, the oil flow rate was increased to mean flow, and the directions of spray were observed for each case. The oil temperature was then increased using the oil heater for the high temperature checks. The pressure drop within the MGB was determined at different inlet oil flow rates by adjusting the flow and measuring the pressures at the MGB inlet and TPTO. The difference between the inlet pressure and TPTO pressure gives the required pressure drop. For the oil flow rate measurement at still higher temperature, the test was carried out with alternate oil simulating the viscosity of OX-38 oil at 120°C, in order to avoid hazards of handling hot oil. The MGB inlet oil flow rate was then adjusted to the maximum flow, and oil from various branches spraying out from the oil jets were collected one by one to measure the oil flow rate for the respective jet.

2.2 Wipe tests for contact pattern development of the spiral bevel gear mesh

Iterations of contact pattern tests were carried out till the achieving of satisfactory contact pattern with the required shimming and grinding corrections. The Tooth contact pattern development test (Wipe Test) was conducted in Quasi Static conditions, to arrive at the acceptable contact pattern. The objective of the test was to arrive at the acceptable contact pattern for gear & pinion in terms of size & location, and to establish the required machine setting data for production of pinion for gear pair. This was a pre-requisite for further dynamic and endurance load tests. The contact patterns were checked for each step after dis-assembly of the gearboxes from the rig.

No-load contact pattern for the gear teeth was prepared at the assembly shop at the gearbox build stage. After this, the MGB was subjected to quasi-static wipe tests on Wipe Test Rig (see figure 4). The test rig was designed for application of and measurement of torques (at quasi-static speed by using a motor with speed reduction stage), as well as rotor load application and measurement for the various steps as per test requirements.

The test rig set up consisted of a Rotor mast loading block, Input and TPTO Bracket assemblies, Brake Motor with speed reduction gear box, Pulley arrangement and Specimen mounting fixture (Test cart). A variable speed drive motor was integrated with the speed reduction gear box connected to a flexible cardan shaft which in turn connected the rotor mast loading unit of the rig. The specimen MGB was assembled on the trolley with pylon struts and tie rods. The trolley with MGB specimen was assembled with rotor mast loading block, input bracket and TPTO bracket of the Wipe test rig.
The torque loading system consisted of rope & pulley arrangement assembled on the Input bracket and TPTO brackets of the Wipe test rig. The ropes on Input and TPTO were locked with wire lock adapters assembled on Input and TPTO brackets. The other end of the wire ropes of Input and TPTO brackets were hung with weighing pans and calibrated weights were added to apply the required torque, after which the drive motor was switched on for slow speed/quasi-static rotation. Torque transducers were connected at flanges of Input, TPTO and Hydraulic pinion for Torque measurement on MGB. Strain gauging was done on four pylon struts & three Tie rods, and load calibration was carried out in in both directions. Strain values were measured by means of strain measurement system using data acquisition software. Moments & thrust loads were applied using hydraulic jacks. The applied moments & thrust loads were measured through load cells attached to the hydraulic actuators of the Rotor mast loading block. After completion of each load case, the MGB was sent to the gearbox assembly shop for modular level disassembly and recording of the contact pattern.

2.3 Functional tests for establishing the lube oil parameters

A functional test rig was designed and fabricated for functional testing of the MGB as per requirements of measuring the basic parameters like oil pressures, oil flow rate, gearbox housing and sump oil temperatures and vibrations, before subjecting the MGB to full load tests. The rig comprised structural items, speed step up rig gearbox, drive system and motor. The test rig also comprised of a flushing unit for MGB, rig lubrication tank and a structure to mount AC Drive motor and speed step up rig gearbox. The structure was isolated from floor by providing shock mounts. The required power to MGB input was obtained from the AC Drive motor and speed increasing adapter gearbox. The Test rig Lubrication system provided lubrication to the speed increasing adapter gearbox through hydraulic hose connections. A
A high speed helicopter flexible shaft was assembled in between the speed increasing adapter Gearbox shaft to MGB Input shaft. The test setup sketch is shown in Figure 5.

![Schematic arrangement for MGB Functional Test Rig](image)

Figure 5: Schematic arrangement for MGB Functional Test Rig

The measurement setup consisted of Flow meter, Thermocouples, accelerometers and Pressure sensors for the measurement of Flow, Temperatures, Vibrations and Pressures on the MGB respectively. Virtual instruments via software on PC monitor were used as indicators to measure the following parameters during the test - Body temperatures on Conical housing Bearing locations on Freewheel housing, Input and TPTO housing, MGB housing, Accessory housing, Cooler fan, Temperature at inlet to the Oil Cooler unit, Sump oil temperature, Temperature at outlet to the Oil Cooler unit, Flow measurement at inlet to cooler unit, pressure at Outlet of the Lube oil Pump, Tail Power Take off, Input to MGB, Oil cooler inlet, Oil cooler outlet, Vibration Pickups on Conical housing in X,Y,Z directions, Input housing in Radial directions, TPTO housing in Radial directions, Accessory housing in Radial directions, Cooler fan Bearing in Radial directions and RPM at MGB input. A PC based data acquisition system was installed to acquire and save the test data continuously during the run. As a safety measure for the test rig and the specimen under test, all the test rig parameters and specimen parameters were interlocked with the drive system to safely trip the test when the parameters exceed the limits specified.

First the speed increasing test was carried out wherein the MGB was filled with oil and run by increasing the speed in steps of 5%, 10% to reach 100% speed. Both Flow and Pressure started building simultaneously with increase in speed. During the test run the absence of leakages at all interfaces, and the MGB parameters were monitored and recorded. After achieving satisfactory initial conditions, MGB was run at 100% speed for 1 hour. During the run all MGB parameters were monitored and recorded for every 2 minutes of interval till the temperature reached stabilization. The MGB parameters like temperature of housing surfaces
at various bearing locations, sump & ambient temperatures, Vibrations, Time trace and FFT, oil flow rate and pressures were recorded. Subsequently an accelerated cycle test run was carried out wherein the MGB was accelerated to 125% speed and held for 30 seconds. Then, it was decelerated to 100% and held for 60 seconds. A total 50 cycles of test run was carried out and parameters were recorded. During the test, the MGB was observed for any abnormal noise. During the run, the leakages at all interfaces and MGB parameters were monitored and recorded.

Further, an oil quantity optimization test was carried out on the MGB with inclinations of forward tilt, rear tilt, right tilt and left tilt with reference to the Rotor axis. For each of the above inclinations, the MGB was run till the stabilization of sump oil temperature was reached. During the run, the leakages at all interfaces and MGB parameters were monitored and recorded for every 2 minutes. The test was further continued for determination of undrainable volume and unused oil quantity in MGB housing, oil filter, cooler and hoses.

2.4 Endurance Load Testing of MGB

The test was carried out on an MGB test stand specially designed for conduction of load test by application of closed loop torques, mast loads and accessory loads at the required rpm. The rig was housed in a separate test facility, and comprised of the Test Rig Structure, a Multi-drive system, Rig Gear boxes, Rotor Mast loading block, Hydraulic Actuators, Accessory loading systems, Control & monitoring system, Data acquisition system, Sensors for pressures, flow, temperatures, mast loads, torque, speed & vibration measurements.

Initially, static strain survey tests & dynamic wipe tests were conducted on MGB assembly to evaluate the strain values on MGB with the actual mounting plates and Torque reaction parts. During the test, various combinations of mast loads and thrust loads were applied on MGB. The test stand sketch is shown in figure 6.

During the endurance load test the MGB speed was increased gradually in steps by increasing the speed of an AC motor used as prime mover. Prior to applying loads on the MGB, a warm up run was carried at no load to observe functional parameters of MGB. The rotor mast loads, torques and accessory loads were applied as per the load spectrum to carry out the endurance runs.

For running the MGB, an AC induction motor controlled by variable frequency drive (VFD) was used as a prime mover. The AC motor was mechanically coupled to the MGB input flange via suitable flexible couplings and Engine line test rig gearbox. By varying the input frequency to the motor, speed was varied from 0 RPM to the required RPM. The torque application on Input and TPTO was through an electrically closed loop loading system where the electrical energy is re-circulated in a closed loop. For this, two AC induction generators were mechanically coupled to MGB main rotor shaft & Tail power output shaft via suitable flexible couplings, and controlled by separate AC drives connected to a common DC bus used for producing electrical power proportional to the torque required by regenerative braking, where mechanical energy was converted into electrical energy. The powers thus generated by regenerative braking during the test were fed back to the mains/grid, thus constituted an electrically closed loop system. Hence, the power drawn from the mains during testing is required only to overcome frictional losses in the mechanical system, thereby significantly reducing mains power demand and operating cost of the testing. Since the test rig is of electrically closed loop type, it can accommodate changes in teeth ratios in the Main
Gearbox during the development phase, thus making it flexible in nature. The torques were measured by torque sensors mounted in line with input & TPTO shafts. The speed increasing/decreasing test rig gear boxes with suitable gear ratios ensured that required RPMs at MGB input and at AC generators were obtained. A specimen fixing carriage used for MGB assembly, thus completing the test set up. The generators used for application of torque at TPTO were mechanically coupled to the MGB flanges via flexible cardan shafts.

The specimen carriage was used to assemble and prepare the MGB outside the rig. After assembly the carriage was pushed inside to align the MGB shafts with test rig gear box shafts (input & TPTO) and the cardan shaft connecting to upper gear box. The entire structure was isolated from ground by providing mechanical shock mounts. The test stand was positioned inside sound proof room with sound proof sliding doors and viewing windows. The lubrication system for intermediate gear boxes, hydraulic system for application of rotor mast loads & for loading hydraulic accessory pumps were placed at basement below the test rig for easy return of rig gearbox oil by gravity flow. External forced air cooling was used to cool the specimen under test during the load test to maintain the MGB temperatures within the specified limit.

Figure 6 : Schematic arrangement for MGB Load Test Rig
For rotor mast load & thrust loads electronic pressure controllers were used, which regulated the proportional pressure valves mounted in hydraulic lines for each hydraulic jacks so that each jack was controlled independently such that any combination of loads could be applied on each jack. A programmable logic controller (PLC) was used in order to automate/control the sequence of activities up to the readiness to start the actual run. These activities included starting of cooling pumps for motor & generators, switching on lubrications for intermediate gearboxes, switching on hydraulic system for MGB accessory pumps, switching on hydraulic pumps for Rotor Mast Loading system, confirming the on-line status of the data acquisition system and bringing the multi-drive system to the “ready” mode. The PLC ensured that the “drive ready” status was reached only after the switching on all the motors, pumps, pressure & flow switches and ensuring the online status, the data acquisition system etc. The current feedback from generators to the drives maintained the torques always steady during the test. The encoder feedback from the motor to the drive always maintained constant speeds without fluctuations. As a safety factor, the control section also included protective functions such as over current, over voltage & over temperature protection circuitry. During the load test all the flight conditions were simulated as per the load spectrum. Since the testing involved the loading of MGB under dynamic conditions, a variable speed AC motor was used to rotate the MGB in the required speed and direction. The speed at the MGB input & TPTO were measured by speed sensor mounted at MGB input & TPTO shafts.

Simulation of rotor mast loads & moments: Simulation of rotor loads & moments involves designing of a mechanical system to make the application of loads on a rotating part possible with the help of loading device fixed onto the static test rig structure. This rotor mast loading system was therefore visualized in the form of rotor mast loading block with thrust bearings, having four lugs at which hydraulic jacks are attached. By having independent control over the hydraulic jack load, it became possible to apply the required combination of rotor mast loads & also the moments. The rotor mast loads were measured by the jack load cells.

Simulation of accessories loads: The accessories loads like alternator, two hydraulic pumps and oil cooler fan were simulated during the test. For this the original helicopter items were used on the MGB. The alternator was loaded by using external resistance load bank, where the energy was dissipated in the form of heat. The hydraulic pumps were loaded by using an external pump loading system.

Safety features: An interlocking system was provided for each of the measured parameters for tripping the drive and releasing all the loads in case of safety limit of any parameter exceeds during the test. Also a video monitoring system was provided to monitor & record the run continuously during test. All the sensors, conditioners & data acquisition systems were connected to UPS power to take care of power fluctuations as well as to prevent loss of important test data in the event of power failures. As a safety factor, the control section also included protective functions such as over current, over voltage & over temperature protection circuitry. A shear neck flange with supporting bracket assembly was introduced between MGB flange and the rig gearbox. This shear neck flange acted as a mechanical fuse to prevent sudden load spikes or over load, if any.

The MGB load test called for continuous monitoring of the following various parameters during the test: RPM of MGB specimen, Pressures at inlet, TPTO & outlet, Oil flow rate, Strain values at different locations on housing & MGB mounting parts like Z plates, Torque
strips, Temperatures at various locations like bearings, housings and oil sump areas, Vibration levels at various locations, Rotor mast loads applied by each of the 4 rotor mast loading jacks, Torque values at MGB input & TPTO, Loads on Tie-rods, pylon struts, and FFT & Time trace for vibration parameters. In addition to the parameters called for the test specifications, it was equally important to continuously monitor the satisfactory performance of the test rig by monitoring various key parameters.

In view of the large number of parameters involved a PC based data acquisition system was used to monitor and acquire data continuously by means of data acquisition via Lab-view program. For the safety of test rig and specimen, all the instruments/sensors were calibrated prior to the start of tests.

Following the above endurance tests, acceptance functional and load testing was carried out on new gearboxes made to the final configuration for the prototype tests. The typical gear tooth contact patterns obtained are shown in figure 7.

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<tr>
<th>Contact pattern for gear tooth - at no load</th>
<th>Contact pattern for pinion tooth - at no load</th>
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<tr>
<td>Contact pattern for gear tooth – after load test</td>
<td>Contact pattern for pinion tooth – after load test</td>
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Figure 7 : Typical gear tooth contact patterns obtained

The endurance load tests were carried out according to a load spectrum comprising of steps corresponding to the loads experienced by the MGB during flight, including maximum continuous power (MCP) and take off power (TOP) steps. After passing these tests, the MGB was assembled onto the LUH prototypes for further helicopter system and flight tests.

3.0 Conclusion

Special test set ups were prepared for the testing of the Main Gearbox of Light Utility Helicopter as per the test programs, and extensive testing was carried out in the various test stands indigenously developed at HAL. The feedback from all these tests was used to finalise the design of the helicopter main gearbox for use during the prototype testing phase of the helicopter.

References:

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