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Evolution of an Overhaul Methodology for a High Speed Combat Aircraft Gearbox

Hafeezur Rahman.A[1], Santosh P Sugate[1],S.Ganesan[2]
[1] *(Scientist D, CVRDE, DRDO, Ministry of Defence, Avadi, Chennai-54, Tamilnadu, India)*
[2] *(Scientist G, CVRDE, DRDO, Ministry of Defence, Avadi, Chenai-54, Tamilnadu, India)*

Abstract: *Overhaul is a methodology whereby a system undergoes periodical maintenance to achieve its intended design life. It is also a mandatory requirement for any aircraft system to obtain type approval and airworthiness certification. Developing such a maintenance methodology for an aircraft system is challenging due to conflicting requirements, lack of standard procedure and adoption based on similarity. Although, literature suggests different approaches such as condition monitoring, MSG approach, MIL standards etc. the best solution for evolving this methodology seems to be a combination of MSG approach, historical failure data, test bed data, and flight data. To explain the way in which this methodology is evolved, a combat aircraft gearbox is considered as a case study. This gearbox and its functional details are presented first, followed by the sequence of overhaul. Overhaul components such as fault diagnosis, testing, cleaning, inspection, fits & clearances, assembly, storage etc. are explained in detail followed by their logical evolution through illustrations. Finally, by implementing this overhaul methodology the MTBO life of the gearbox was increased by the certification agencies along with benefits such as reduced time for airworthiness clearance, ease of overhaul & training and reduced queries from production agencies was achieved.*
***Keywords*:** *accessory gearbox, overhaul, fault diagnosis, snags, strip examination, cleaning, inspection, testing*

I. Introduction

Overhauling is a process by which a system is removed, disassembled, cleaned, inspected, repaired and tested as per approved methodology with the aim of increasing the systems useful life. On a macro scale, this sequence for the system seems to be the same irrespective of its type of application. However, on a micro scale this methodology becomes complex and time consuming if several constraints such as extreme operating environment, high safety, and high reliability etc. are imposed on the system. Such requirements are mandatory for any in-service aircraft line replaceable unit (LRU) to be certified airworthy and obtain type approval, which certifies the system fit for induction for Indian Air force [1].To conform to such stringent requirements, the overhaul program for the LRU should cater to the following.

a) Capability to detect all types of nascent abnormalities, defects and impending failures. This factor assumes significance if the system possess high criticality or no redundancy which is common in single engine aircraft systems. Hence, for such a LRU if 100% inspection and testing is carried out as a part of overhaul, it may ensure airworthiness but unnecessarily increases mean time to overhaul (MTTO).
b) Ensure maximum mean time between overhaul (MTBO) to increase system availability. This is possible provided the systems overhaul life coincides with the major system such as an engine overhaul or calendar servicing.
c) Ensure minimum mean time to repair (MTTR) which not only increases system availability but also facilitates technology transfer. In addition, this methodology must be unambiguous to avoid queries in the form of part disposition orders (PDO) from manufacturing sources.
d) Reduce time for airworthiness clearance from certifying agencies. One of the primary reasons for this is the lack of acceptable limits and to avoid this, acceptable limits for individual parts and fits & clearances for assembly are mandatory in the MRO method to avoid delay in airworthiness.
e) Facilitate ease of training for the aircraft maintenance crew and to do so the overhaul procedure has to unambiguous to avoid inordinate delays or wrongful practices, which affects airworthiness.

Developing an overhaul methodology incorporating all these above factors is challenging due to certain conflicting requirements, such as reduced time to repair/overhaul and detect all types of defects at the same time. It follows that to detect all types of defects, a lot of testing and fault diagnosis is required which consumes time and hence some means to detect snags with minimum possible time has to be evolved. In addition, there are no standard acceptable limits for parts or fits and clearances for assembly as the wear pattern varies between systems and platforms. Against this backdrop, it is clear that the overhaul methodology for any aircraft system has to be evolved based on standard condition monitoring techniques, aviation practices, prototype and flight-testing and one such methodology evolved for a high-speed accessory gearbox for combat aircraft application forms the objective of this paper.

II. Literature Review

There are different approaches available in literature to formulate an overhaul methodology for a gearbox namely condition monitoring, maintenance system group approach (MSG-2) & (MSG-3), military standards, handbooks and manuals. In addition, overhaul manuals of contemporary fighter aircrafts, federal aviation regulation (FAR), and performance data from test bed and flight trials provide valuable information to develop overhaul methodology for the gearbox. The details of some of these techniques are given below.

Condition monitoring: It is a technique to carryout periodic and continuous measurements on the system and resulting data interpreted to indicate the condition of the system and thereby determine the need for preventive maintenance. Various signals emanating from the gearbox are used to determine the gearbox health and predict any impending failures. Although various techniques are available across the world, the commonly used techniques for aircraft gearboxes are vibration, noise, SOAP analysis, lube parameters and visual inspection [2].

Vibration analysis is the most common condition monitoring technique recommended for gearboxes. Here the acceleration spectrum is captured at specific points on the gearbox using accelerometers and techniques such as Fast Fourier Transform (FFT) applied to display a frequency spectrum, from which gearbox problems can be identified using distinct frequency components. By trending vibration periodically from gearbox, it is possible to detect and diagnose incipient damages so that maintenance can be planned and executed in the gearbox. Some of the mechanical faults that can be identified include unbalance, hunting of gears, shaft misalignment, cracked gears, worn gears, excessive backlash, general looseness etc. using the vibration trouble-shooting chart [3] as given in Table.1 below.

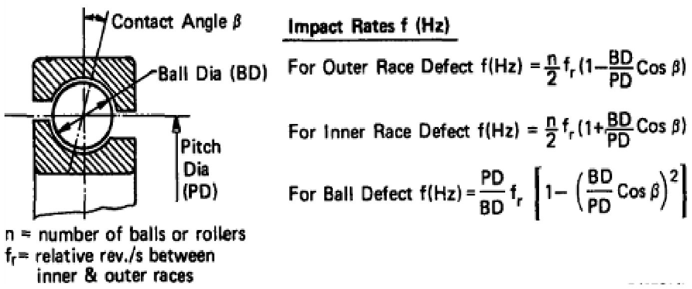
Table.1 Vibration trouble shooting chart for gearbox

Dominant frequency	Nature of fault	Direction
1X	Unbalance	Radial
2X, 3X & sometimes 4X	Misalignment or bent shaft	Radial & Axial
2 to 60 kHz	Damaged rolling element bearings	Primarily radial
1/2 or 1/3X	Loose journal bearings in housing	Primarily radial
42 to 43% of X	Oil film whirl in journal bearing	Primarily radial
Shaft critical speed	Hysteresis whirl	Primarily radial
Tooth mesh frequency (No. of teeth x shaft rpm)	Damaged or worn out gears	Radial & Axial

In the above, 'X' represents the running frequency of the gear or shaft determined by converting rpm into frequency using the formula:

Running frequency (X) in Hz = [Shaft rotational speed in rpm / 60] (1)

Similarly, the distinct frequency within the range 2-60 kHz used to detect the source of defects in bearings whether from inner race, outer race, or rolling element [4] is determined using the formula:



In addition, side band analysis and regular tracking of vibration amplitude (P_k or RMS in g) provides a history or vibration trend for the gearbox, which can be used to determine acceptable limits.

The second most common condition monitoring technique for gearbox is noise measurement where the noise generated by the gearbox is recorded and analysed to determine system health. This noise is generated due to several factors such as gear mesh stiffness changes, dynamic mesh forces, frictional force effects, air pocketing, lubricant entrapment and most importantly transmission errors in gears [5]. This noise that can be recorded by a sound level meter at periodic intervals can be used to form an acoustic history of the gearbox, which similar to vibration can be used to determine acceptable limits. When a deviation is observed in this trend, it reflects abnormalities, which can also be used for fault diagnosis. This acoustic analysis also reflects the change in gearbox vibration as both are inter-related which is given by:

$$\text{Noise in dB} = 20 \log_{10} [a/a_{ref}] \quad (3)$$

Where a is the vibration recorded in m/s^2 whereas a_{ref} is the reference amplitude with value of 10^{-6} m/s^2 [6].

The third common technique used for condition monitoring is spectrometric oil analysis program (SOAP) which involves microscopic analysis of constituents of the lube oil used in the gearbox. This technique is based on the approach that contaminants and wear particles collect in the lube oil thus providing vital clues regarding the health of the gearbox. This process is carried out in three stages namely sampling, analysis and reporting. Whereas in the sampling stage used oil of 2 to 3 ounce is collected in a clean container, in the analysis stage this oil sample is subjected to a spectrometer that grades the oil and provides information regarding metals, contaminants and water present in the sample in ppm. This report is then interpreted to identify changes inside the gearbox and offer suitable countermeasures along with trending the data for deriving acceptable limits. The common causes for wear metal particles in the lube oil [7] are given in Table.2 below.

Table.2 Causes for wear metal particles in gearbox lube oil

Components responsible	**Metals**							
	Fe	**Cu**	**Ni**	**Cr**	**Ag**	**Mg**	**Al**	**Si**
Bushings		*						
Anti-friction Bearings	*				*			
Gasket material & sealants				*				*
Gears	*	*	*					
Pump casing		*					*	
Pump shaft	*				*			
Gearbox casing						*	*	*
Ingested dirt								*
Shafts	*	*	*					

The fourth condition monitoring technique that can be used on the gearbox is lube parameter tracking. Gearboxes have lube systems that supply oil to gears, bearings, splines, seals etc. for lubrication. In case this supply is inadequate it results in rapid wear of the components which may lead to reduced life or failure such as scoring which needs to be avoided. Hence, lube parameters such as oil pressure at pump delivery, low oil pressure, flow, and temperature shall be frequently monitored to determine system health along with trending to determine acceptable limits for these parameters.

The final condition monitoring technique that is widely used to determine system health is visual inspection. This is carried out on a system level, which means that this technique determines system health without the need for a tear down inspection. To do so, the checkpoints used are oil leakage, filter clog, size of ferrous particles in lube system using magnetic chip detector (MCD).

Maintenance system group (MSG) approach: The MSG approach is a methodology designed for the maintenance of civil aircraft and its systems by a consortium of airline manufacturers in 1968. Until date, three documents have been released which detail this methodology as given below.

a) Maintenance Evaluation and Program Development Handbook (MSG-1)
b) Airline/Manufacturer Maintenance Program Planning Document (MSG-2)
c) Airline/Manufacturer Maintenance Program Planning Document (MSG-3)

The MSG-1 approach is a process-oriented approach whereby each component in the system was categorised according to its maintenance requirement as hard time (HT), on condition (OC) and condition monitoring (CM). As CM has already been discussed, let us describe the other two methods. Whereas, HT applies to a component that needs to be replaced upon completion of calendar life or flight hours, OC applies to components that will be replaced only upon need based on its condition. Upon this categorisation, logic trees are designed based on detailed failure modes and analysis. This methodology also called as a bottom-up approach is time consuming as the system needs tear down inspection to decide on HT, OC or CM. Hence, MSG-2 approach overcame this drawback by adopting a top-down approach, which increased both system availability and reliability [8]. The last of the series namely the MSG-3 revision 1 & 2 improved upon it predecessor, is the present day standard to determine scheduled maintenance requirements for new airplanes. In addition, it includes detailed decision logic for assigning maintenance tasks and task intervals. When designing the overhaul methodology for a combat aircraft gearbox, the MSG-3 approach was found to be most advantageous because it not only minimised MTTO/MTTR but also maximised MTBO. In addition, it structured maintenance logics that are easily understood by maintenance crew which are some of the main objectives of a successful overhaul methodology.

Military handbooks, standards, & manuals: Military handbooks [9, 10] issued by the US DOD provide useful insight into the overhaul instructions for aircraft engines and related accessories such as engine gearbox, PTO etc. Although these standards provide general information for systems such as accessory gearbox, it is still a very useful tool for both sequencing the methodology and inspection checkpoints. Two standards [11, 12] that pertain specifically to aircraft accessory gearbox provide detailed insight into various aspects of design such as incorporation of sub-systems, health monitoring, acceptance, and endurance testing. In addition, these standards also provide useful insight into the basis of acceptance, which is useful while developing an overhaul methodology. Finally, two military manuals [13, 14] by DOD provide vital information regarding the overhaul manual preparation and organisation of caution notes and instructions.

III. System Considered For Overhaul

The system, for which the subject methodology is applied, is an accessory gearbox that forms a part of the secondary power system (SPS) of a combat aircraft. Secondary power system (hydraulic, electrical, pneumatic power) in turn draw on engine power to supply their client systems with non-propulsive power in all those cases where functions are not directly actuated by the pilot's muscle [15]. The input power to this SPS is through a power take-off shaft (PTO) which connects both the engine and accessory gearbox in the aircraft. The client systems for this SPS consists of two hydraulic pumps, one integrated drive generator (IDG), and one jet fuel starter (JFS) mounted on this gearbox as shown in Fig.1 below.

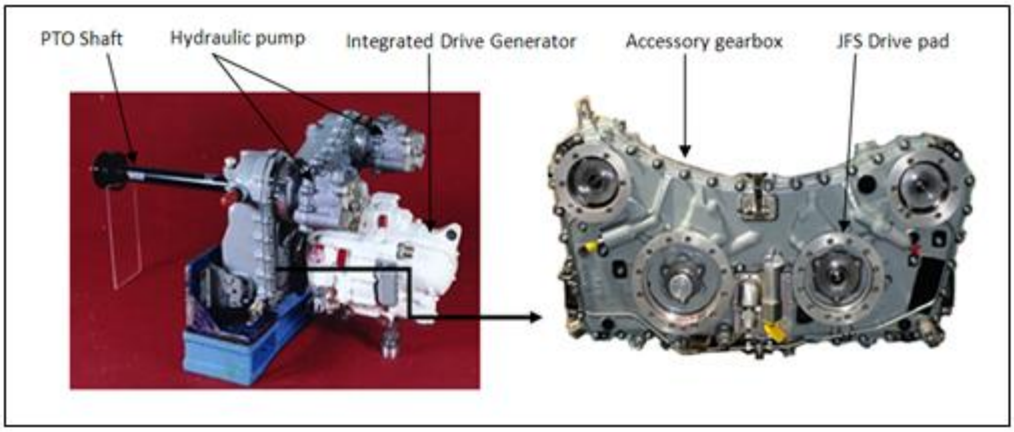


Fig.1 Gearbox with and without accessories

These two hydraulic pumps supply hydraulic power for actuating the flaps, ailerons, slats, landing gear, nose wheel steering, wheel brake, air brake, hydraulic motor driven pump, and hydraulic motor driven generator for emergency operation. Whereas, the IDG supplies standby electrical power to the systems, the JFS is used only to start the engine and remains idle once the engine attains self-sustaining speed. Thus, the accessory gearbox performs twin functions, one to start the main engine through the JFS and the other is to run the accessories mounted on it to cater to the electrical and hydraulic power requirements of the aircraft.

This gearbox is a single input, multi-output gearbox consisting of simple and compound spur gear train. This gearbox operates at a rated speed of 16810 rpm with a maximum power transmission capability of 185 kW. To provide ease of assembly and disassembly, the gearbox casings are made in two parts, namely main and cover casing made of magnesium alloy. To provide lubrication, the gearbox houses an in-built lube sump with one pressure; two scavenge pumps along with a fine filter with pop-out indication. Finally, health-monitoring systems such as low oil pressure (LOP) & high oil temperature (HOT) switches and two magnetic chip detectors (MCD) are provided in this gearbox.

IV. Case Study - Overhaul Methodology For Aircraft Gearbox

The sequence in which the overhaul methodology is carried out for the accessory gearbox is given as follows.

Insitu examination: Once the subject gearbox is sent for overhaul, the first step is to carry out a visual examination for signs of mechanical damage and paint peel off along with fretting corrosion on the input shaft. To check for any mechanical looseness, all the casing studs are checked for their torque tightness followed by an engagement check for the over running clutch that engages and disengages the JFS with the gear train. Once all these steps are completed, the gearbox is checked for its function at a lower input speed of 6000 rpm (approx. 35-40% of rated speed) with no load, prior to a full load test to check for oil leakage at casing interfaces. These insitu checks are the first step in basic fault diagnosis where visual, mechanical looseness, clutch engagement, oil filling and oil leakage are checked.

Fault diagnosis & testing: Once insitu checks are completed, the next step is to carry out fault diagnosis of the gearbox at test beds. However, to check the gearbox for all faults require extensive testing at different test rigs which increases MTTO. The gearbox has undergone all these tests during acceptance testing and hence repeating them is unnecessary. Hence to solve this problem, a history of snags that have occurred during endurance testing at test bed and flight trials were collected as shown in Fig.2 below.

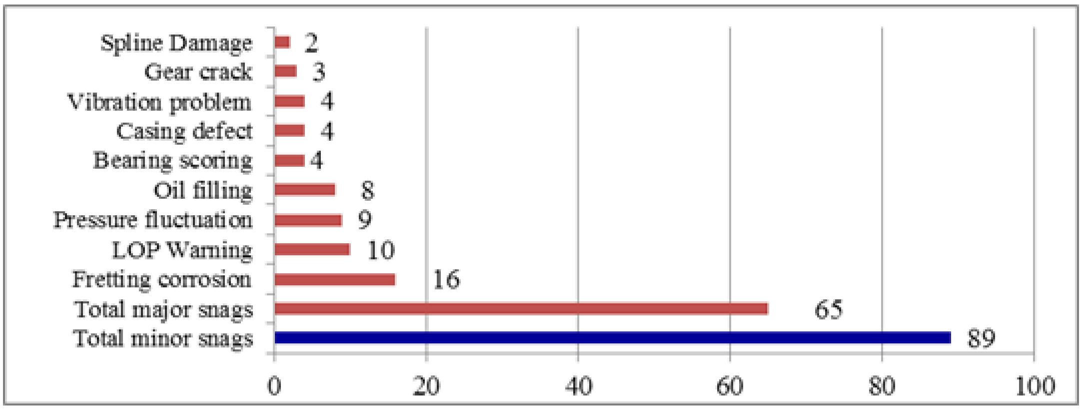


Fig.2 Snag/defect data reported on the gearbox

The above snag history exhibits two types' namely major and minor snags. Major snags are those that can be rectified only at the base workshop or production centre whereas minor snags can be rectified even at the hanger. In addition, minor snags can be incorporated in the form of checkpoints during strip examination whereas major snags need root cause analysis, in order to incorporate them in the fault diagnosis. Hence, a root cause analysis was carried out using the nine-step approach [16] and the results are tabulated in Table.3 below.

Table.3 Root cause analysis of major snags

Major snag	Location	Root cause	Fault diagnosis method
Fretting corrosion	Input shaft	Low wear resistance & oxidation	Visual
LOP warning	Last lube jet in cover casing	Inadequate suction head at high altitudes	Test rig
Oil filling	Lube sump	Lack of interconnection between sumps	Visual
Vibration problem	On mounts	Excess clearance/ defective gears & bearings	Test rig, visual, NDT & dimensional
Pressure fluctuation	Pump delivery	Lube oil lines interconnected	Test rig & Flexoscope
Bearing Scoring	On inner & outer raceway	Sand particles	Test rig & visual
Casing defect	Lube line	Sand particles & steel shots in lube line	Visual & Flexoscope
Gear crack	Pump gears	MnS inclusions & H_2 embrittlement	Test rig, visual & NDT
Spline damage	Starter shaft	High hardness of mating shaft	Visual & dimensional

Except fretting corrosion, oil filling, casing defect and spline damage all other snags shown above need the gearbox to be tested in test beds to confirm these defects. Although different test rigs are available to carry out acceptance testing for the complete gearbox, repeating these entire tests is unnecessary. Hence, the gearbox has to undergo only minimum performance test in two test rigs namely the endurance test rig and the attitude test rig to identify all the relevant major snags.

The endurance test rig as shown in Fig.3 is used to test the gearbox performance at different speeds and loads. It consists of a DC motor, which acts as a prime mover that runs the test gearbox through a step-up gearbox. This test gearbox is mounted on a frame through three mounts that simulate actual mounting conditions along with hydraulic dynamometers that simulate actual accessory loadings on the gearbox. Whereas in the endurance test rig the gearbox does not undergo any translation, in the attitude test rig the gearbox is subjected to pitch and roll.

In this attitude test rig, there are two tables namely the pitch and roll table inside, which the test gearbox is mounted as shown in Fig.4. Both these test rigs collectively help in carrying out fault diagnosis at different conditions. The different speeds at which the gearbox is driven are 9100 rpm, 11000 to 16000 rpm at increments of 1000 rpm and 16810 rpm in both coast up and coast down mode. Loads applied vary proportionately as per the speeds and various parameters such as speed, load, lube pump pressure, flow; lube oil temperature, oil leakage, vibration, noise etc. are monitored.

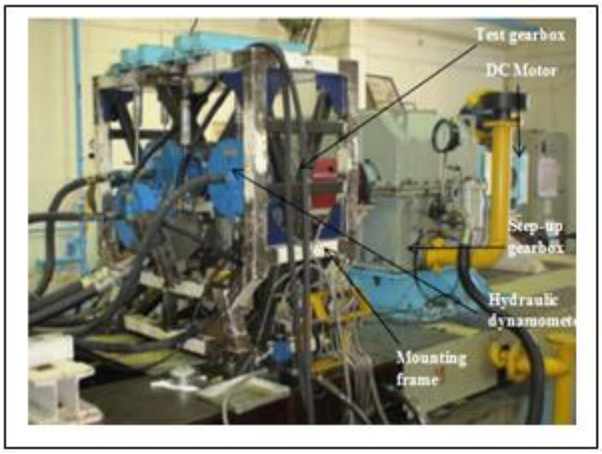


Fig.3 Endurance test rig

Fig.4 Attitude test rig

During performance test in the endurance test rig, the vibration amplitude is monitored at three points namely the mount LH, RH and input boom of the gearbox. The FFT captured during this test displays a frequency spectrum from which gear defects and bearing defects can be identified. For example, the gear crack that is shown as a major snag is identified by first calculating the fundamental frequency using (1). Based on this fundamental, the other components are calculated as shown in Table.1 and these frequency components are checked in the FFT to identify defect. The consolidated frequency component table for all the gears in the gearbox at rated speed is shown in Table.4 below.

Table.4 Consolidated frequency component table for gears at rated speed

Gear	Fundamental in Hz	Defective gear frequencies in Hz			
		2X	3X	4X	Gear mesh frequency
Input gear	280	560	840	1120	8680
Gear CI LH-1	189	378	567	756	8694
Gear CI LH-2	189	378	567	756	2268
Idler LH	93	186	279	372	5859
Gen gear LH	133	266	399	532	5852
Pump driver LH	100	200	300	400	5900
Gear CI RH -1	202	404	606	808	8686
Gear CI RH-2	202	404	606	808	5858
Pump driver RH	100	200	300	400	5900
Idler RH	98	196	294	392	5880
Pump gear LH & RH	100	200	300	400	1100

By monitoring all defective frequencies that are due to unbalance, misalignment and damaged tooth, major snags can be avoided. Similarly, for all the bearings in the gearbox a consolidated frequency component table that includes inner race, outer race, and rolling element frequency components are developed. However, displaying this consolidated table is too exhaustive and hence only a sample calculation as per (2) for a ball bearing fixed on input shaft LH side alone is given for illustration. This bearing has 10 balls with ball diameter of 9.525 mm, pitch diameter of 54 mm and contact angle of 12^o. For rated speed of 16810 rpm, the frequency calculated as per (1) is 280 Hz. Taking all these values into account the inner race, outer race and rolling element defect occurs at 1643 Hz, 1160 Hz and 1541 Hz respectively.

The noise values recorded for this gearbox as per procedure corroborate with vibration amplitude values as per (3). However, the acceptable limits for both vibration and noise cannot be extrapolated and has to be determined based on data for various gearboxes. Hence, 10 such gearboxes were chosen and from these data, the geometric mean and standard deviation {σ} were calculated for vibration and noise [2]. Whereas the geometric mean represents the acceptable value, the ±3σ represents tolerance for these values. It was found that all gearboxes adhere to these values thus indicating the efficacy of this methodology. The same methodology was carried out to determine acceptable limits for other parameters namely lube oil pressure, flow, and temperature. By determining the acceptable limits for lube pump pressure, it was found that a variation of 0.5 to 1 bar at a particular speed is acceptable. If this variation is beyond one bar, it indicates pressure fluctuation or abnormality in the lube system, which needs thorough tear down inspection of the casings. This fault diagnosis procedure described above only indicates the presence of faults, whereas the extent or damage due to these faults can only be ascertained during tear down inspection.

Teardown inspection: When the gearbox is sent for tear down inspection, the various components are stripped as per recommended procedure and cleaned prior to inspection. In this regard, three types of cleaning are followed as given below.

a) Magnesium casings are subjected to pressurized oil cleaning and ultrasonic cleaning in kerosene for one-hour duration.
b) Gears, shafts and other components are first cleaned using trichloro-ethylene and then subjected to ultrasonic cleaning in kerosene bath for one-hour duration.
c) Ball and roller bearings are cleaned using white spirit until traces of dirt and oil disappear.
d) All titanium components should be cleaned with lab grade acetone to prevent hydrogen embrittlement.

Once the gearbox components are cleaned using the above procedure, the components are subjected to various types of inspection as shown in Fig.5 below.

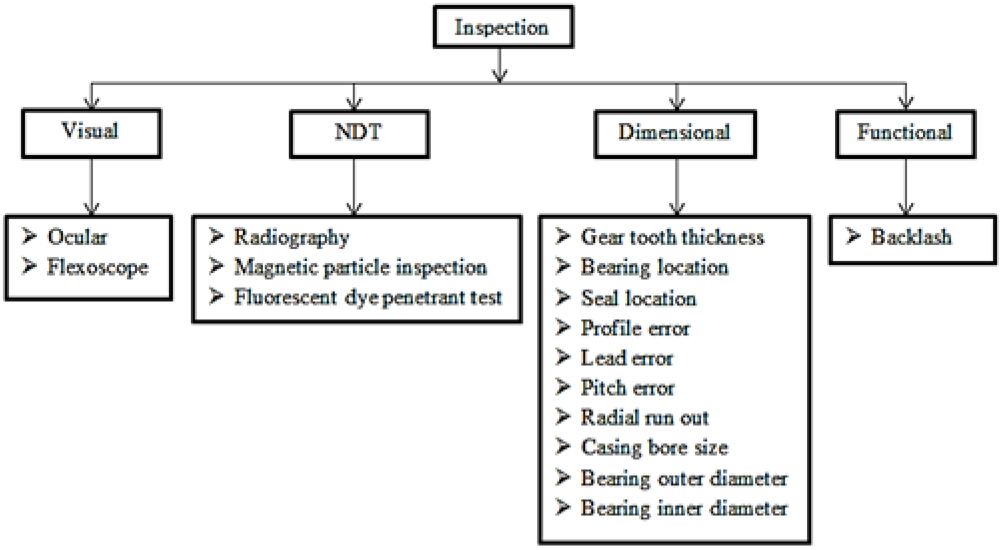


Fig.5 Types of inspection performed during gearbox overhaul

During visual inspection as shown above for gears, several types of defects such as pitting, scoring, flaking, fretting, notching, discolouration etc. are checked on both loaded face and flank of the gear tooth. However, scratches are accepted or rejected based on their depth and orientation. Any scratch that can be picked by a chisel edge style of radius 0.5 mm across width is not acceptable. Similarly, any scratch that extends from tip to root direction is not acceptable which most likely will promote failure in the future. For shafts only fretting, coating peel off, dent and scratches are inspected which are not acceptable if rectification is not possible.

The visual inspection procedure for ball and roller bearings are different from the general methodology adopted above. For bearing, its surfaces are classified into functional and non-functional ones. Functional surfaces are those which severely affect the bearing performance [17] such as roller element surfaces, shoulders, raceway, bearing OD & ID surfaces, cage pilot etc. whereas all other surfaces are graded as non-functional and subjected to different acceptance criterion as shown in Table.5 below.

Table.5 Acceptance criterion for functional and non-functional surfaces on bearings

Defect type	Functional	Non-functional
Corrosion & rust	Not acceptable	Not acceptable
True brinelling	0.4 x 0.75mm	Not felt by 1 mm feeler gauge
False brinelling	0.4 x 0.75mm	Not felt by 1 mm feeler gauge
Pitting	Diameter < 0.5 mm & spaced < 14 mm	Diameter < 0.5 mm & spaced < 14 mm
Nicks & dents	Not acceptable	Not felt by 1 mm feeler gauge
Scoring	Width < 0.5 mm & not crossing	Width < 0.5 mm
Scratches & scuffs	Not acceptable	Width < 0.5 mm
Skidding	Not acceptable	NA

The other type of visual inspection is flexoscope or flexible boroscope that is used to inspect the minicore oil galleries of the casings in the gearbox. This visual inspection is critical, since there are locations where the suction lines of the pressure pump and scavenge pump intersect as shown in Fig.6 which cause pressure fluctuation that is a major cause of snag discussed above. Once this snag is identified during fault diagnosis and testing, it is confirmed during this visual inspection to prevent false alarms. This type of visual inspection not only detects defects such as lube line interconnection but also defects such as sand or steel shots in the suction lines of the pump, which is major snag as described above.

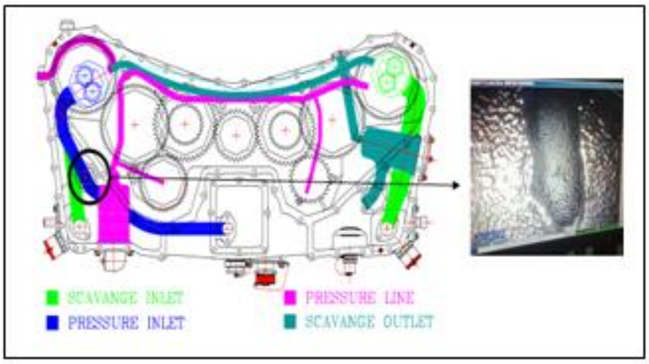


Fig.6 Visual inspection of casing & defect identified

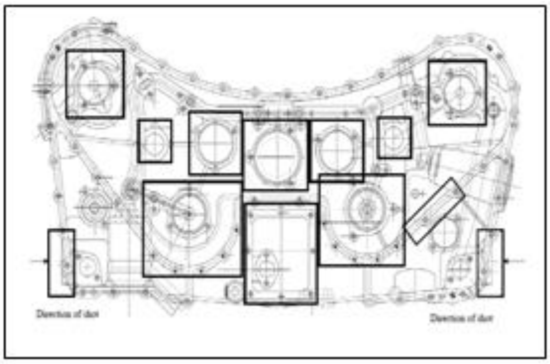


Fig.7 Radiography of gearbox casings

As shown in Fig.5 three types of non-destructive testing namely radiography, magnetic particle inspection (MPI) and fluorescent dye penetrant test (FDPT) are carried out on the components. Of these, radiography is applied only on the casings, MPI to the gears and FDPT to non-magnetic components. Radiography for the main and cover casings are mandatory, as these are Class 1 casings, whose failure will contribute to both loss in human life and platform [18]. Hence, selected areas on the casings based on performance history are identified and radiography carried out as shown in Fig.7 to 2% sensitivity as per ASTM-E-155 standard.

The second type of NDT namely the MPI is carried out on all gears and shafts to identify cracks especially on the root that are capable of causing tooth breakage or shear as shown in Fig.8. This test carried out as per ASTM-E-709-08 standard confirms the failure that has already been identified using vibration condition monitoring. Finally, the FDPT test carried out as per ASTM-E-165 standard for non-magnetic critical components on the gearbox along with other NDT tests ensure that no defects are left undetected thus ensuring airworthiness. Once the visual and NDT are completed for casings, gears, shafts and other components they are subjected to dimensional measurement.

However, when each component has a multitude of dimensions only certain critical dimensions that affect functionality such as backlash, vibration, and noise alone are inspected. Whereas acceptable limits for individual errors such as profile, lead error etc. are provided in the overhaul methodology, no limits are provided for casing bore diameter, shaft outer diameter, gear bore diameter and bearings outer and inner diameter. The reason for this is that individual tolerance on diameter serve no purpose provided the mating fits are not maintained. Hence, these dimensions once measured are put into a fit and clearance chart to determine it acceptance as shown in Fig.9 below.

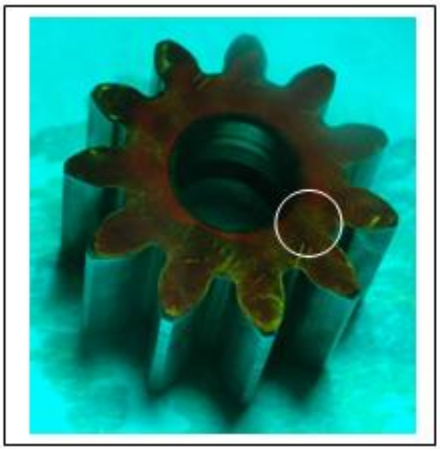


Fig.8 Gear crack identified by MPI

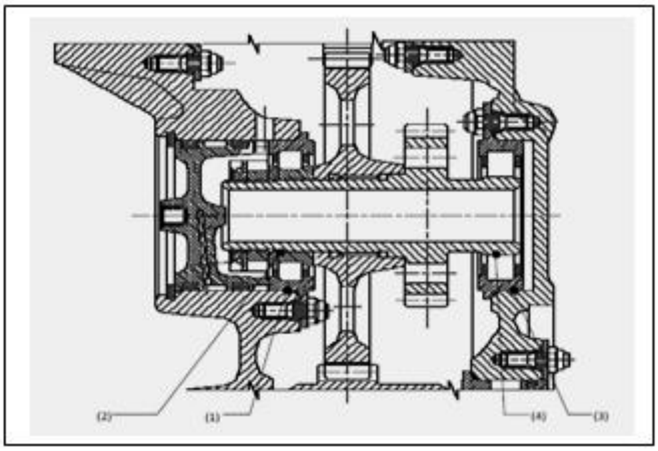


Fig.9 Gear assembly for fit & clearance illustration

In the gear train shown above, four different fits have been displayed in numbered sequence. The first fit {1} refers to the fit between the LH bearing OD and casing ID whereas {3} refers to the fit between bearing RH OD and casing ID. Similarly, {2} and {4} refer to the fit between the shaft OD and bearing ID in the LH and RH side respectively. For this gear train, the fit & clearance chart is generated as shown in Table.6 below. In this chart, it is observed that whereas the clearance between the casing and bearings increase the clearance between shafts and bearings are relatively unchanged. The reason for this variation is the mating material; whereas the casings are made of magnesium, the shafts and bearings are made of high strength steel. In addition, the maximum allowable clearance shown is based on the data obtained from prototype gearbox that underwent 1000 hrs of endurance testing and standard one-third tolerance rule. Accepting components based on this fit & clearance method is reasonable rather than absolute tolerance, which ensures that components are satisfactory from a form, and fit angle but perform unsatisfactorily from a functional aspect.

Table.6 Fit & clearance chart for a typical gear assembly

Fit No	Location	Original limits				In-service wear limits		Max allowable clearance
		Dimensions		Assembly clearance		Dimensions in mm		
		Min	Max	Min	Max	Min	Max	
1	LH bearing OD	51.991	52.000	--	0.007	51.991	52.000	0.011
	LH casing ID	51.985	51.998			51.985	52.002	
2	LH bearing ID	24.994	25.000	--	0.002	24.994	25.001	0.004
	LH shaft OD	24.998	25.005			24.997	25.005	
3	RH bearing OD	51.991	52.000	--	0.007	51.991	52.000	0.011
	RH casing ID	51.985	51.998			51.985	52.002	
4	RH bearing ID	27.269	27.275	0.015	0.025	27.269	27.275	0.025
	RH Shaft OD	27.250	27.254			27.250	27.254	

Gearbox assembly: Once teardown inspection is completed, the components either old, salvaged or CAT 'A' are assembled into the gearbox as per approved procedure. This re-build gearbox is subjected to the same testing procedure discussed in the fault diagnosis section to check for any assembly related defects. Prior to despatch for flight trials the last condition monitoring technique that is performed on the gearbox is oil analysis or SOAP analysis discussed below.

SOAP analysis: As discussed during condition monitoring techniques, the SOAP analysis technique provides not only fault diagnosis but also wear pattern for components. This analysis has to be performed on the gearbox at two stages, first during in-situ testing and the final during post-assembly testing prior to despatch. However, there are no standard acceptable limits for trace elements and it has to be evolved for individual systems based on test experience as shown in Fig.10 below.

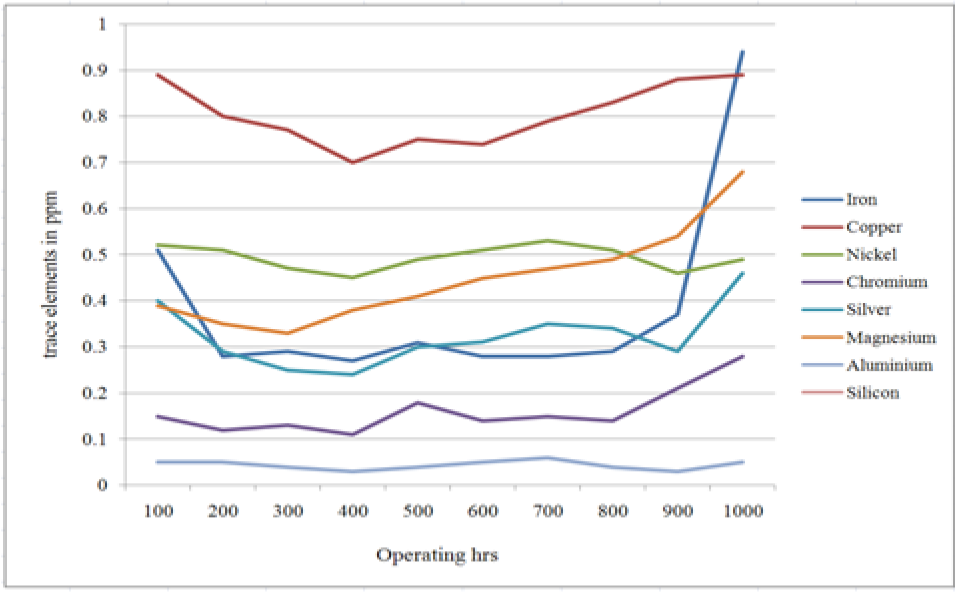


Fig. 10 SOAP data for endurance gearbox

From the above data, it is clear that for iron, the concentration levels are higher during initial 100 hrs, remains constant upto 900 hrs, and then increases drastically beyond 900 hrs. This pattern is similar to the bathtub curve where the first 100 hrs, next 800 hrs and last 100 hrs correspond to the infant mortality, useful life and wear out period respectively. In addition, only magnesium exhibits such pattern other than iron. Other than silver, copper and silicon other trace elements are insignificant as they are alloying elements for the gear and bearing material. Whereas silver correspond to the coating given on pump shafts, copper corresponds to the bearing bushes and hence their trend gives an indication of the pump wear which can be corroborated with tear down inspection. Finally, the absence of silicon shows that the gearbox has operated without any sand/dust impurities in its lube oil, which tend to promote scoring in gears and bearings. Finally, using these trends acceptable limits for trace elements can be determined based on the maximum value observed during endurance testing.

V. Conclusion

The approach by which the overhaul methodology of an aircraft LRU is evolved has been explained in detail with a combat aircraft gearbox as a case study. Although different maintenance methodologies exist for civil aircraft systems as seen in the literature, to develop one such requires extensive data along with standard condition monitoring techniques. It was demonstrated that by carrying out failure investigation of historical snags, useful inferences could be drawn which in-turn improved fault diagnosis and reduced testing time. In addition, to determine component usability, inspection of only critical dimensions was required and the best usability of a component during overhaul was in assembled condition rather than from individual dimensions as demonstrated in the fit & clearance chart. Further, SOAP analysis of trace elements in the lube oil serve to corroborate the observations during fault diagnosis and tear down inspection. Overall, the data obtained from prototype, endurance, and flight-testing help to develop a robust overhaul methodology that will facilitate airworthiness and type approval for the gearbox. Finally, by developing this methodology and demonstrating it successfully on various gearboxes, the MTBO of the gearbox was increased from 100 hrs to 500 hrs, MTTO reduced from several months to few weeks, PDO's reduced, facilitated training, and airworthiness clearance thus serving the basic overhaul objectives of an aircraft LRU.

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