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ABSTRACT

There is a strong economical motivation for monitoring the health of expensive or safety critical systems. This is particularly true for commercial and military aircraft where maintenance costs follow not too far behind fuel costs in overall operating expenses. Most of the operating costs are engine related for fixed wing aircraft. Diagnostic monitoring is a particularly strong thrust in the growing helicopter market. Here maintenance costs associated with the transmissions and drive train greatly increase the mainteance burden and failure risk. Detection measurements fall under two general categories of vibration and particle detectors. The latter are more amenable to tracking wear. There are presently many military programs evaluating diagnostic systems. Greater attention and documentation is now being given at overhaul to wear and failure modes. Some very useful studies have been conducted on the wear and failure modes of particular aircraft. Wear debris analysis can supply a great deal of information such as: particle concentration, rate of change in concentration, composition, particle size and shape, principal metals, etc. It is not economically feasible to monitor all variables. At least one role of the lubrication and wear specialist is to provide guidance in selecting the most appropriate variables to monitor. He must further be involved in the problems of prognosis. How will the wear condition change with continued running, and what condition calls for some action?

THE REDUCTION OF DIRECT operating cost of commercial and military aircraft is becoming an increasingly important thrust for future aircraft design. The use of engine condition monitoring systems has substantial potential in reducing unnecessary maintenance action and improving flight readiness and safety.

Diagnostic systems can monitor engine performance through gas path pressure and temperature measurements and fuel flow measurements. They can also monitor the condition of mechanical systems containing bearings and gears. Corrosion and wear play an important role in failure and component replacement. The objective of this paper is to review the failure modes of aircraft oil wetted parts, particularly in helicopter engines and transmissions, and to highlight some of the health monitoring concepts and diagnostic devices.

The influence of various wear modes in aircraft has impact on safety, performance, and life. Generally performance, as measured by specific fuel consumption (SFC), has not been a crtical factor influencing engine scheduled overhaul. However, with increasing fuel costs there is a growing concern over performance retention over the engine life. Presently, fuel cost account for 45% of the operating expenses of domestic wide body aircraft like the 747 and DC-10. Wear activity contributing to performance degredation include erosion of turbine blades and wear of shaft seals and gas path seals. A clearance change of only 1% of blade height affects specific fuel consumption 1.5 to 2%. While SFC is indeed an economic concern, the impact of wear on the cost of unscheduled maintenance and the time between overhaul (TBO) is substantial enough to make complex diagnostic systems worthwhile. This is particularly true for helicopters where the mechanical and dynamic complexity is much greater than fixed wing aircraft. Here, high speed gas turbine engines drive low speed rotors through light weight high torque transmissions. In addition, helicopters operate over a large number of high temperature cycles and in dirty environments. The TBO for helicopter engines is on the order of 2000 hrs. compared to 10,000 hrs. for fixed wing aircraft. The added mechanical burden of the transmission and drive train make maintenance a more critical issue than performance. According to (1)* the drive system alone accounts for 30% of the direct maintenance costs. The primary purpose of diagnostics of oil wetted parts is to reduce unscheduled maintenance, increase time between overhaul and create an opportunity for "on-condition" maintenance.

ENGINE WEAR MODES

Many of the engine maintenance problems are related to bearings and seals. A study of the T53 and T55 engines (2) shows that 37% of unscheduled maintenance is due to seals. This is generally in the form of carbon wear. Coking also occurs when pressurization air at idle drops causing oil to leak past the carbon seal. Of the oil wetted parts, bearings are the most critical component accounting for 25% of unscheduled repairs. These are followed by gears and splines. Early versions of these engines generated wear particles from outer ring rotation. Wear also occurs between the cage and bearing ring. A more serious problem is associated with roller skewing. This produces particles from roller end wear but it can also cause catastrophic failure of the cage. Most cage failures are too sudden for diagnostics to be effective. The event usually results in total engine failure and possibly forced landing.

Beerbower (3) has listed the relative frequency of various wear modes from the investigation of (4). These include low cycle sliding fatigue, rolling fatigue and abrasive wear. The dominant wear mode was sliding fatigue (54%) which includes roller skidding damage, cage wear and nonclassical spalling due to excessive load or manufacturing errors. Corrosion is not specifically categorized in some studies but in the military it is generally felt that presently it accounts for as much as 30% of bearing removals.

As will be discussed later, debris is a major cause of component wear and deterioration. Airborne debris accelerates compressor and turbine blade erosion. The dirty environments encourtered by helicopters has led to the development of inlet particle separators which has improved the mean-time-between-depot-returns (MTBD) for erosion from 3000 hrs. in 1966 to over 100,000 hrs. in 1973 (2). Erosion is now a problem in the separators themselves.

Dirty air from compressor bleed can get into bearing cavities and produce debris damage to bearing surfaces which can lead to surface initiated fatigue. There is also some concern about compressor blade/shroud wear particles entering the bearing cavities.

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*Numbers in parentheses designate References at end of paper.

TRANSMISSION WEAR MODES

Studies of transmission failures reveal that bearings are the most sensitive component. Peterson et al. (5) and (6) condensed the data of (7) and showed that the frequency of component malfunction is: bearings 46%, gears 23%, liners 15%, misc. (shaft, clutches, lube system, etc.) 16%. A greater variety of wear modes are present in the transmission than in the engine because of the larger number of gears and their characteristic wear modes. Beerbower (3) has summarized the frequency of wear modes for bearings and gears for two transmissions (UH-1 and CH-47) from the data of (7) and (8). This is shown in table 1. The dominant wear modes as well as the frequency of component malfunction show different patterns for each transmission. This is true for engines as well as transmissions and it continually changes with time as corrective modifications are made. Both transmissions show greater malfunctions with bearings than gears. The UH-1 encounters more abrasion than the CH-47 which is more sensitive to rolling fatigue. Corrosion is common to both.

The studies clearly show that classical fatigue failure of bearings is rarely observed. Bearings are generally removed because of other competing failure modes such as corrosion, debris denting and manufacturing defects (grinding furrows). In addition, the advent of clean bearing materials (vacuum arc remelt and degassing processes) has reduced the probability of classical subsurface initiated fatigue. Bearing life is now seen to be more surface sensitive. Gears tend to be a little more tolerant of surface defects than bearings. They also are a source of debris generation along with other components producing sliding wear or fretting (splines and bearing race/housing interfaces). In general, the wear of gears and splines do not reduce their ability to function. Their wear particles, however, cause secondary damage to other components like bearings which are more sensitive to debris. A transmission research engineer from the U.K. has concluded that "cleanliness is godliness." To avoid secondary and progressive damage due to contaminants a U.S. manufacturer is using a modular transmission design separated by filter screens. The sensitivity of bearings to debris damage and the substantial abrasion mode of wear in transmissions as shown in table 1 has motivated the Army to initiate a program on oil debris analysis and superfine (3 μm) filtration (9).

DIAGNOSTICS

Condition monitoring procedures involve the three key elements of detection, diagnosis and prognosis. Detection must reveal an abnormality such as excessive wear. Diagnosis further clarifies the abnormality as to what component may be experiencing a malfunction. Prognosis is the act of foretelling the rate of deterioration and when corrective action should be taken.

Of the many detection methods that are available there seems to be three general statements that can be made. First, the concepts used in the various detection devices are generally complimentary. Second, the deficiencies encountered in the field are being corrected through improved designs. Third, the success of the diagnostic device can only be achieved if it is sensitive to the critical failure modes of the mechanical system.

There are two general classes of detection methods for oil wetted parts: vibration or vibration related (such as shock pulse) and oil (or particle) analysis. Vibration related methods are attractive because they are simple, inexpensive and not affected by filtration level or the use of grease rather than oil. Oil analysis, however, is more sensitive to wear and will be considered in more detail here.

Lubricating oil, in addition to acting as a lubricant and coolant, carries with it information that it has collected by way of wear particles or oxidation products as it journeys through the oil wetted parts. The concept of oil analysis is based on the premise that the type of wear or debris particles, if collected and analyzed, is indicative of the wear and surface condition of the internal components. Sampling alone presents substantial problems due to: settling of particles, adhesion to component walls, filtration and other factors affecting consistant, timely and useable samples. Once a debris sample is obtained there is a great deal of information (generally more than practicable) that can be obtained from them. These can be characterized by: concentration of particles, rate of change of concentration, dominant metals present, distribution of various metals, particle size distribution, particle shape and chemical form (e.g., metal, oxide, metallo-organic). Despite the difficulties in sampling and the limited range of particle sizes that detection devices operate in, the various oil monitoring techniques have been relatively successful. Some of these techniques are briefly described below.

SOAP - Spectrometric oil analysis program (SOAP) is widely known and has been used for many years in the U.S., U.K. and Canada. Periodic oil samples are taken from engines or transmissions. These are examined spectrographically for metal type and concentration. The method is sensitive to particles smaller than 10 μm. It has limited ability to isolate faults. The general feeling in the military is that SOAP is approximately 80% effective in isolating engine failures and perhaps a little less effective with transmissions (3). A factor influencing the lack of SOAP success is the time involved in the logistics of sampling, shipment and laboratory analysis. Some aircraft require a SOAP analysis after every flight. There is currently interest in developing a portable SOAP analyzer which can be taken on-board.

CHIP DETECTORS - chip detectors are use extensively in helicopter engines and transmissions. The contain a magnet and are positioned in the oil system to collect ferrous debris for periodic inspection and trend monitoring. Chip detectors are most effective in collecting large particles (25 μm to over 500 μm) that may come from fatigue spalls. Experience seems to indicate that more failures are accompanied by relatively large particles (>50 μm). For this reason chip detectors compliment SOAP which can more appropriately monitor the smaller particles and normal wear conditions.

Chip detectors can give on-board fault indication. Metal particles which bridge the gap between two electrodes in the chip detector activate a warning light. It is well known that there are a large number of false indications with these devices (many chip lights have been disconnected). The warning light will go on regardless of whether the gap is bridged by a large number of small particles, a small number of large particles or a single long narrow particle. This problem has been effectively resolved by the use of a capacitive discharge burnoff chip detector (10). When the gap between the electrodes is bridged a strong current pulse from a capacitor is discharged which causes local melting of the fine particles ("fuzz") that cause false readings. Larger particles will continue to bridge the gap giving a true reading. These types of detectors used in a full-flow-through mode within the oil system appear to be quite promising.

FERROGRAPHY - Ferrography is a more recent development (11). A small sample of oil is allowed to flow over a glass slide located over a high gradient magnet. Magnetic particles such as iron and iron oxide are precipitated out with the larger particles located at the entry point. The particle size range is on the order 0-20 μm. The prepared slide can be examined under a special microscope using bichromatic illumination which reveals metal in red and oxide in green or yellow. Further analysis can be done with the scanning electron microscope and other surface analytical tools to determine chemical and elemental content (12). This is an excellent laboratory tool which can distinguish between various particle morphology and wear modes. It is called an Analytical Ferrograph.

A simplified version, known as the Direct Reading Ferrograph, uses optical density measurements to determine the amount of wear. A more recent version, the Real-Time Ferrograph, was developed for on-board monitoring.

IN-LINE OIL MONITOR - A technique which has had some success in engine condition monitoring of oil wetted parts employs the principles of light scattering for particulate debris detection and light attenuation for chemical and thermal degradation (13). This system has been tested in the TF41-A-2 engine as part of a total inflight engine condition monitoring system (14). It provides greater information than some other on-board systems and is effective over a large range of particle sizes, but appears to be quite expensive.

RADIOACTIVE ISOTOPE TAGGING - This method is not frequently used but is very effective in isolating faults in critical components. One example of its use has been to monitor cage wear of an engine bearing (2). A silver isotope layer is deposited below the normal silver plating. When the silver wears beyond a critical level the silver isotope is released into the oil system and detected by a Geiger Mueller counter. This method is also being used to monitor the roller end wear of a critical main shaft engine bearing of a military engine.

EFFECT OF FILTRATION

There is evidence that an ultra clean oil system can increase bearing life considerably through a reduction of debris damaging surface stress raisers (15). The quantitative effect of improved filtration on life is not clearly documented, but the trend is certainly there (16). At least the appearance of bearing surfaces and the amount of sludge has improved with finer filtration (9).

Filtration down to the 3 μm level removes most of the particle information used in many oil monitoring methods (17) and periodic oil sampling becomes ineffective. Alternative measures must then be taken. These could include continuous on-line monitoring upstream of the filter or a system which incorporates the filter as part of the detection device.

PROGNOSIS

Good diagnosis is helpful to prognosis which involves the prediction of residual life or function of a component based on the wear trend and mode that has been observed. Many components, when considered failed, have been preceeded by a progression of deterioration due to wear over a period of time. This is the basic premise of diagnostics through particle analysis. Beerbower (3), using his model for various wear modes has predicted qualitatively the rate of accumulated wear with time. Sliding fatigue wear and corrosive wear proceed rather slowly with time. The rate of abrasive wear and particularly scuffing wear increases with time and occurs more rapidly. Rolling fatigue wear occurs quite rapidly with not a great deal of advanced warning once a fatigue spall is formed. Even then safe operation may still be available for hundreds of hours.

Future mechanical components may be characterized by different wear modes or at least a different distribution of wear modes. This could occur as the result of surface treatments (for debris tolerance), new lubrication concepts and operation in different regimes of severity. As an example, advanced engines are proposed that operate at much higher speeds which with currently used materials, can cause catastrophic fracture of bearing rings as the result of crack propagation from a surface fatigue spall.

CONCLUSIONS AND FINAL COMMENTS

1. The use of appropriate diagnostic tools for aircraft oil wetted components has good payoff in the reduction of direct operating costs through reduced unscheduled maintenance. Diagnostics is a means by which the practice of regularly scheduled maintenance can be transformed into on-condition maintenance.

2. Diagnostics is particularly important in helicopter engine and transmission systems where reliability of oil wetted parts are a significant factor in direct operating costs. Bearings account for the majority of failures. They are more sensitive to secondary damage from debris than gears.

3. There are several useful diagnostic methods for oil or wear particle analysis. They are generally effective over a limited range of particle sizes but tend to compliment each other if used in parallel.

4. Fine filtration (<40 μm) has the potential of increasing time between overhaul, but reduces the effectiveness of oil monitoring techniques if conventional sampling methods are used. Alternative diagnostic techniques or at least sampling methods, must be used. Further diagnostic modifications may have to be considered for future aeronautical systems which may incorporate more grease lubrication, self-lubricating materials, sealed-for-life components and mist lubrication.

5. The development of a diagnostic system should be parallel and integral with the development of a mechanical system. Diagnostic measurements must accompany bench tests of components for ultimate reliability and effectiveness of both.

6. A diagnostic technique like ferrography has benefitted the science of tribology as much as the science of tribology has helped it become an excellent diagnostic tool. Greater collaboration between designers of mechanical systems, designers of diagnostic systems and tribologists would be beneficial.

REFERENCES

1. A. J. Lemanski, National Aeronautics and Space Admin., Washington, D.C., Dec. 1976, NASA CR-145114.

2. P. A. King and R. L. Givens, U.S. Army Air Mobility Research and Development Lab., Fort Eustis, Va., May 1977, USAAMRDL-TR-77-9.

3. A. Beerbower, U.S. Army Air Mobility Research and Development Lab., Fort Eustis, Va., Jan 1975, USAAMRDL-TR-74-100.

4. K. G. Rummel and H. J. M. Smith, U.S. Army Air Mobility Research and Development Lab., Fort Eustis, Va., Aug 1973, USAAMRDL-TR-23-28.

5. M. Peterson, C. Bowen, and D. Minuti, "Aeronautical Analytical Rework Program, Helicopter Transmission Contamination Study," Interim Report, Contract N62269-75-C-0499, Analytical Rework/Service Life Project Office, Naval Air Development Center, Warminster, Pa., June 1977.

6. M. Peterson, J. McGrew, T. Harrington, and C. Bowen, "New Approaches for Service Life Improvements Covering Navy Helicopter Transmissions," Contract N62269-75-C-0031, Analytical Rework/Service Life Project Office, Naval Air Development Center, Warminster, Pa., Mar 4, 1975.

7. J. J. Dougherty and S. J. Blewitt, U.S. Army Air Mobility Research and Development Lab., Fort Eustis, Va., Sep 1973, USAAMRDL-TR-73-58.

8. C. W. Bowen, L. L. Dyron, and R. D. Walker, U.S. Army Air Mobility Research and Development Lab., Fort Eustis, Va., Jan 1971, USAAVLABS-TR-70-66.

9. D. Lubravo, U.S. Army Research and Technical Lab., Fort Eustis, Va., Private Communication, May 1979.

10. T. Tauber, In "Mechanical Failure Prevention Group, 26th Proc., NBS-SP-494, Detection, Diagnosis and Prognosis," Shives, T. R.; Willard, W. A., Eds.; National Bureau of Standards: Washington, D.C., 1977; p 123.

11. W. W. Seifert and V. C. Westcott, Wear 1972, 21, 27-38.

12. W. R. Jones and R. J. Parker, ASLE Trans. 1979, 22 (1), 37-45.

13. G. F. Skala, In "Instrumentation for Airbreathing Propulsion, Progress in Astronautics and Aeronautics," Vol. 34, Fuhs, A. E.; Kingery, M., Eds.; Massachusetts Institute of Technology: Cambridge, 1974; p 499.

14. L. R. DeMott, AIAA Paper 78-1472, Aug 1978.

15. H. Dalal and P. Senholzi, ASLE Trans, 1977, 20 (3), 233-243.

16. S. H. Loewenthal and D. W. Moyer, J. Lub. Tech., 1979, 101 (2), 1979, 171-179.

17. R. Valori, In "Mechanical Failure Prevention Group, 26th Proc., NBS-SP-494, Detection, Diagnosis and Prognosis," Shives, T. R.; Willard, W. A., Eds.; National Bureau of Standards: Washington, D.C., 1977; p 49.

Table 1. - Relative Frequency (%) of Wear Modes

in UH-1 and CH-47 Transmissions

	UH-1		CH-47	
Wear Mode	Bearings	Gears	Bearings	Gears
Sliding fatigue[a]	0	19.01	5.97	8.24
Rolling fatigue[b]	14.12	1.95	29.08	0
Adhesive	0	11.72	4.55	4.82
Corrosion	20.99	2.48	25.80	9.46
Abrasion	22.19	3.27	2.74	0.64
Fretting	4.27	0	1.89	6.81
Total	61.57	38.43	70.03	29.97

[a] Low cycle.
[b] High cycle.