

Helicopter Transmission Fatigue Life Estimation

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Prototype equipment developed at the Aeronautical Research Laboratory has been installed in two Royal Australian Navy Sea King helicopters to estimate the tooth-bending fatigue life usage of critical gears in the main rotor gearbox under Australian operating conditions. The equipment is capable of monitoring actual life usage of individual gearboxes in "damage" or "life fraction" terms. Some 479 h of in-flight load data covering 227 flights and eight main sortie types have been accumulated. These data have been analyzed and it has been concluded that, for practical purposes, the lives of the gears in the main rotor gearbox are not limited by fatigue. The potential of the fatigue life usage monitoring system for application to individual gearboxes is examined, and desirable enhancements to the prototype equipment are discussed.

Introduction

A RECENT report¹ on helicopter airworthiness indicated that the number of airworthiness-related accidents could be an order of magnitude higher for helicopters than for fixed-wing aircraft over equivalent flying hours.

Present technology dictates that a significant proportion of the rotating machinery in a helicopter cannot be duplicated; this applies particularly to the main rotor and tail rotor systems (e.g., blades, shafts, and gearboxes). It is imperative that in-flight failures of components in these zones be avoided since such failures could be catastrophic.

In recent times, considerable international interest has been shown in the fatigue life usage and the health of non-duplicated elements of helicopter rotating machinery, and the development of a fairly comprehensive monitoring system has been reported.² Compared with the monitoring systems developed and proven for use with fixed-wing aircraft, the status of helicopter monitoring system development is relatively immature. The need for improved monitoring techniques has been clearly identified by the U.K. Civil Airworthiness Authority.^{1,3}

This paper outlines research leading to the estimation of the tooth-bending fatigue life of gears in the main rotor gearbox (MRGB) of Sea King helicopters operated by the Royal Australian Navy (RAN), and the development of a Fatigue Life Usage Indicator (FLUI) system to monitor fatigue life usage during normal helicopter operation. The potential of the FLUI system for use in monitoring life usage of individual gearboxes is examined in this paper, and enhancements to the prototype system to provide an operational unit with improved capability and operator acceptance are outlined in general terms.

Main Rotor Gearbox Fatigue Life

The fatigue failure modes in heavily loaded gearboxes include:

- 1) surface fatigue of rolling element bearings and of gear teeth, producing pitting or spalling on contact surfaces, and
- 2) fatigue fracture at the root of a tooth due to tooth-bending stresses.

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The fatigue life corresponding to each failure mode may be estimated for each relevant component; these estimates provide the data for the estimation of the operating time at which the gearbox should be replaced. Health monitoring techniques, in which various parameters are monitored regularly for signs of an impending failure, are applied as a safeguard against the unexpected (e.g., an undetected flaw in material of construction, the unpremeditated exceedance of rated loading, etc.). If, in the future, health monitoring techniques are developed to the stage where they are capable of providing reliable and adequate warning of impending failure, the importance of fatigue life monitoring would diminish, and "on-condition" maintenance practices could be safely applied for all failure modes. However, with the current status of health monitoring technology, it is widely believed that both "life usage" and "health" monitoring should be simultaneously adopted for improved MRGB airworthiness and improved operational safety.

For many years, the Aeronautical Research Laboratory (ARL) has been involved in studies and advice regarding the airworthiness of MRGB's in helicopters operated by the RAN. In the health monitoring field, ARL work on the analysis of vibration signals has been reported by McFadden and Smith⁴ and McFadden^{5,6} and that on oil and wear debris analysis by Atkin et al.^{7,9}

Regarding fatigue life estimation, surface fatigue failure modes have been investigated by Lewicki et al.,¹⁰ who estimated the surface fatigue lives of the individual bearings and gears in the power train of a turboprop reduction gearbox and, using statistical methods, estimated the life of the complete gearbox. ARL has been concerned with the tooth-bending fatigue modes and has been involved in research¹¹⁻¹⁵ regarding the estimation of the "safe" tooth-bending fatigue lives of gears in the MRGB of the Wessex Mk 31B and Sea King Mk 50 helicopters operated by the RAN. The manufacturer, using design load spectra, had determined that the lives of some critical gears in the MRGB's of both helicopters were limited by tooth-bending fatigue. The substantiation of the fatigue lives under Australian operating conditions for the Sea King is outlined below.

Until "on-condition" maintenance can be applied safely, valid estimation of the "safe" fatigue life of helicopter transmission systems will remain vital both to operational safety and to the formulation of an economic maintenance policy. For fatigue life estimation, two basic sets of data are required. First, gear tooth-bending fatigue data in the form of the number of cycles to failure of any tooth as a function of stress level ($S-N$ curve) are required together with a suitable stress (or safety) factor to define a "safe" curve. Second, the loads experienced by the gears during service must be known. In the design phase, a "best estimate" of transmission loads is used by

the manufacturer; these may vary significantly from those actually experienced during normal helicopter operation. Also, load spectra for a given helicopter may vary significantly according to the type of use; hence, it is usually necessary for each operator to establish his/her own spectra. This aspect is very relevant to the work of ARL.

The lack of commercially available equipment for measuring in-service load spectra led directly to the development of suitable fatigue monitoring equipment by ARL. Three generations of equipment have been developed. The most recent development,¹⁶ referred to as a Fatigue Life Usage Indicator, has shifted the emphasis from transmission torque spectra measurement with subsequent fatigue life estimation to in-flight fatigue life usage monitoring. Operational load data in the form of totalized times spent in contiguous torquebands have also been accumulated and are available for postflight printout. Two prototype FLUI's were installed in RAN Sea Kings in 1982, and some 479 h of transmission fatigue data have been collected. These data have been assessed and used to provide "safe" fatigue life estimates of critical gears.

Design Concepts for Fatigue Life Usage Indicator

The FLUI, developed for in-flight estimation of gear fatigue life usage, incorporates the "safe" fatigue curve data within the stored read-only-memory program of an onboard microprocessor.

The Sea King employs a hydraulic system to sense the torque developed by each engine. In principle, the helical gear axial loading is supported by a "cushion" of oil, the pressure of which is proportional to torque. Torque pressure transmitters convert the pressure signals to analog electrical signals, which are taken to the cockpit torquemeters. To measure in-service loads, the FLUI system senses the torque developed by each engine via high-performance strain-gage pressure transducers inserted in the hydraulic torque transmitter lines. These transducers convert the hydraulic pressure signals to analog voltage signals. Torque measurement resolution provided by an analog-to-digital converter in the FLUI is 0.6% rated torque.

With the preprogrammed manufacturer's gear fatigue data and the in-flight measurements of engine torque, the FLUI provides a real-time estimation and indication of fatigue life usage for four selected gears in the Sea King main rotor transmission system. It also provides in-flight storage and postflight printout of operational load information in the form of the totalized times spent in each of 10 contiguous torquebands for port engine, starboard engine, and total torques, respectively. Torqueband limits used are given in Table 1. The operational load data can be used to

- 1) Assess on a statistical basis the severity of loading to be expected for various sortie types.
- 2) Assess the fatigue life expenditure of the other gears not nominated for in-flight fatigue life usage indication.
- 3) Provide in-service load data of major importance to manufacturers for use in component design and lifing.

The main elements of the onboard data system are the FLUI (Fig. 1) and the printer. The FLUI uses a set of electromechanical counters to provide nonvolatile storage of totalized fatigue life usage for the chosen four gears. The counters advance by one for each microlife unit of life expended. A fifth counter provides storage of total flying time. Automatically at the end of flight or when requested manually by depressing a cockpit-located print button, a printout (Fig. 2) of the operational load data and fatigue life expenditure for the current flight occurs. The printer was carried on board during the data collection period, but this is unnecessary. The prototype system requires that the data be extracted before power is removed from the FLUI.

The following computed information is printed as shown in the sample printout in Fig. 2:

- 1) Total duration (in seconds) for which the torque level for the current flight falls within the 10 torquebands for port, starboard, and total torques, respectively.

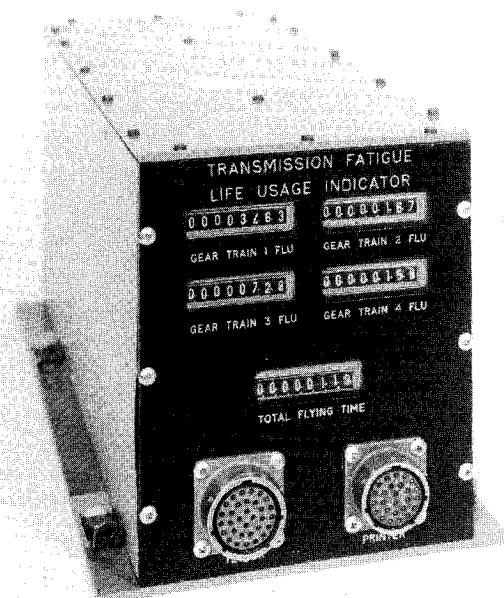


Fig. 1. Transmission FLUI.

| SEA KING TRMLIF 01 | | GEAR | FLU |
|---------------------|------------|----------------|---------------------|
| BAND | DURN (SEC) | G1 | 00012 |
| PORT-0 | 5694.09 | G2 | 00000 |
| PORT-1 | 3007.40 | G3 | 00017 |
| PORT-2 | 0396.61 | G4 | 00000 |
| PORT-3 | 0050.74 | | |
| PORT-4 | 0009.33 | | |
| PORT-5 | 0004.10 | | |
| PORT-6 | 0000.00 | | TOTAL FLYING TIME |
| PORT-7 | 0000.00 | | 11490 SEC |
| PORT-8 | 0000.00 | | 3.1914 HR |
| PORT-9 | 0000.00 | | |
| AIRCRAFT NO N16-118 | | | |
| STBD-0 | 4956.44 | | DATE: 7-10-84 |
| STBD-1 | 3204.31 | | TAKE-OFF TIME: 1320 |
| STBD-2 | 0310.77 | | SORTIE TYPE: G.F.P. |
| STBD-3 | 0005.09 | | |
| STBD-4 | 0000.00 | | |
| STBD-5 | 0000.00 | | |
| STBD-6 | 0000.00 | | |
| STBD-7 | 0000.00 | | |
| STBD-8 | 0000.00 | | |
| STBD-9 | 0000.00 | | |
| COUNTER READINGS | | | |
| TOTL-0 | 5321.02 | GEAR 1: 13266 | |
| TOTL-1 | 4108.30 | GEAR 2: 12710 | |
| TOTL-2 | 1856.32 | GEAR 3: 37295 | |
| TOTL-3 | 0202.13 | GEAR 4: 51832 | |
| TOTL-4 | 0001.23 | TFTIME: 324/95 | |
| TOTL-5 | 0000.06 | | |
| TOTL-6 | 0000.00 | | |
| TOTL-7 | 0000.00 | | |
| TOTL-8 | 0000.00 | | |
| TOTL-9 | 0000.00 | | |

Fig. 2. Sample postflight printout.

Table 1 Torquebands for FLUI (% rated torque)

| Band No. | Individual engine torqueband limits | Total torqueband limits |
|----------|-------------------------------------|-------------------------|
| 0 | 30.2-65 | 15.2-47 |
| 1 | 65-83 | 47-71 |
| 2 | 83-95 | 71-83 |
| 3 | 95-107 | 83-95 |
| 4 | 107-119 | 95-101 |
| 5 | 119-128 | 101-107 |
| 6 | 128-137 | 107-113 |
| 7 | 137-146 | 113-119 |
| 8 | 146-155 | 119-125 |
| 9 | > 155 | > 125 |

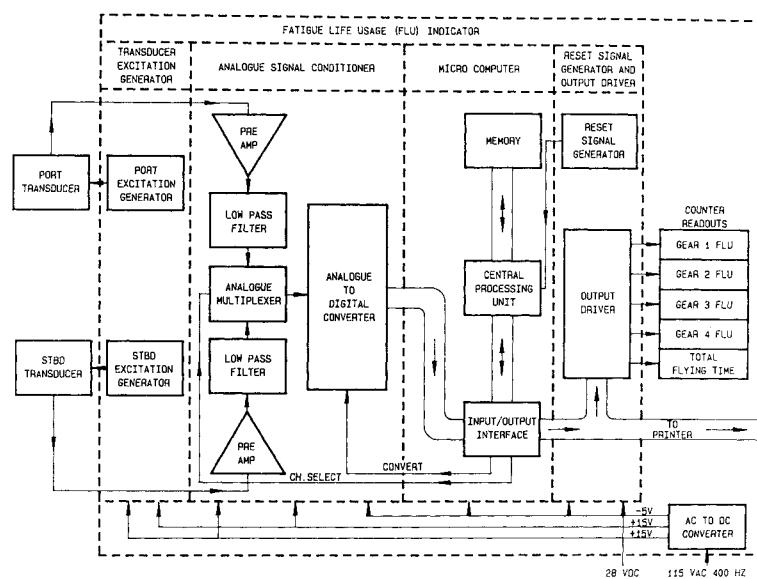


Fig. 3. Block schema of FLUI.

2) Estimated fatigue life usage (in microlife units) for the selected four gears (G1, G2, G3, and G4 of Fig. 2) for the current flight.

3) Total flying time (in both second and hour units) for the current flight.

The remaining information in Fig. 2 is entered manually on the printout by a squadron ground crew in the places indicated by the printed prompts. GEAR 1, GEAR 2, GEAR 3, and GEAR 4 are the cumulative fatigue life usage readings for the respective gears, and TFTIME is the cumulative flying time in seconds.

A comprehensive review of the special demands for an in-flight fatigue life estimation system and the design concepts for FLUI are given elsewhere.¹¹

The principle of operation of the FLUI is illustrated schematically in Fig. 3. The low-level outputs from the pressure transducers are amplified and filtered (with low-pass filters having a cutoff frequency of 22 Hz) to remove high-frequency noise components. The amplifier outputs are passed to a solid-state analog multiplexing switch. Conversion of the selected amplifier output to digital form is provided by an analog-to-digital converter.

System operation is controlled by the microprocessor and associated circuits, which issue conversion commands and allow the two torque inputs to be selected in sequence. Operating programs are stored in programmable, read-only memories. To enable computation of gear fatigue life usage, the gear fatigue relationships are precomputed and entered in look-up tables in the airborne program.

Both port and starboard engine torques are read 100 times/s. During the 10-ms repetition interval, the following actions are performed by the microcomputing system:

1) Fatigue life usage (if any) for each of the four gears under examination is computed, and the life usage increment is added to the contents of associated summing stores.

2) The contents of each of the four summing stores are examined, and, if the respective values are in excess of one microlife unit of usage, the count value of the associated electromechanical counter (Fig. 1) is advanced by 1, and one microlife unit of usage is subtracted from the contents of the relevant summing store.

3) Flying time is advanced by 0.01 s and for each second of totalized time accumulated, the total flying time counter reading is advanced by 1.

4) Torquebands corresponding to the current values of torque are determined for the requisite three spectra and 0.01 s is added to appropriate elements of arrays used to store the basic torque spectrum data.

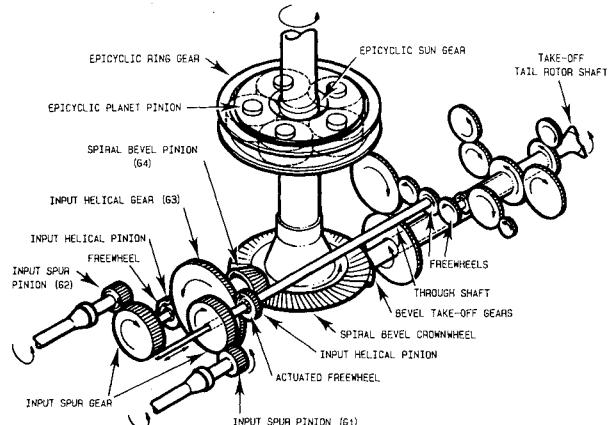


Fig. 4. Sea King MRGB.

When a request-to-print signal is received at the end of the flight, the preceding operations cease and the relevant stored data, after suitable conversion, are transferred to the printer. Transfer of data, as shown in Fig. 2, takes about 60 s.

The instantaneous rate of fatigue life usage may exceed the capability of the electromechanical counters. Ample storage allows any residual life usage to be transferred as soon as the torque level falls.

Application to the Sea King Helicopter

The prototype FLUI systems were installed in RAN Sea King helicopters in 1982. The aims of the program were two-fold:

1) To estimate "safe" fatigue lives (in operating hours) for critical gears in the Sea King main transmission system under RAN operating conditions.

2) To evaluate the prototype data system developed by ARL for in-flight gear fatigue life usage estimation.

The program was concerned basically with the collection of data for a typical helicopter engaged in normal sorties of various types. It was not strictly arranged to monitor fatigue life usage for individual transmissions.

Description of Sea King Main Rotor Gearbox

Two general layouts of the MRGB in the twin-engine Sea King helicopter are shown in Fig. 4. Each engine is coupled to an input spur pinion (G1 and G2) and gear pair, and, hence, through the torquemeter and freewheel unit to an input helical

pinion, with both the port and starboard helical pinions engaging with a single helical gear (G3). The input helical gear (G4) is directly coupled to the spiral bevel pinion and crownwheel pair, which, in turn, is coupled directly to the sun gear of the epicyclic stage, which has a fixed ring gear and five planet pinions mounted on a "spider," which is directly coupled to the main rotor shaft.

The tail rotor and accessory drive power is provided through a bevel gear and pinion, with the former mounted directly below and concentric with the spiral bevel crownwheel.

The rotational speed and the rate of cyclic loading of all gears at 100% rated engine speed are listed in Table 2. For the input helical gear, the load cycles per second listed in the table correspond to single-engine operation; in twin-engine operation, the input helical gear is loaded by both the port and starboard input helical pinions and, hence, receives two load cycles per revolution.

Rated Engine Speed Power and Torque

The rated engine input speed N_R is 18,966 rpm.

The cockpit torque meters indicate values of the port and starboard engine torques via coaxial moving-needle meters calibrated in percentage values. At the rated engine power of 1350 hp at 100% rated engine speed, the indicated torque is 111%.

As the MRGB operates at constant speed, the tooth-root-bending stress is directly proportional to the horsepower P transmitted or to the torque T transmitted, so that either units of horsepower or torque may be used in fatigue life calculations.

Fatigue Stress Factors

Fatigue stress factors¹⁷ agreed between the manufacturer and the airworthiness authority for helicopter gearboxes are: for one to three gearboxes tested, 1.4; for four or more gearboxes tested, 1.3.

In addition, a stress factor of 1.24 is allowable for the input spur and helical gears, provided that three nonfailures were obtained during the appropriate fatigue tests.

Fatigue Curves

The shape of the power vs cycles-to-failure ($P-N$) curve was established by the manufacturer¹⁸ from the results of fatigue tests to failure on a sample of 47 Wessex tail rotor gearboxes. A crack or fracture at the root of any tooth was deemed a failure, and the fatigue life of individual gears ranged from 5×10^4 to 2×10^7 load cycles. The median curve of the 47 results could be adequately represented by

$$P = P_0(1 + AN^{-C}) \quad (1)$$

where P_0 = endurance limit, i.e., power level for infinite fatigue life, and A and C are numerical constants.

As the gears in the Sea King helicopter have similar geometry and material properties to those in the Wessex tail rotor gearbox, this shape for the $P-N$ curve was adopted by the helicopter manufacturer in a fatigue substantiation program for the Sea King MRGB and by ARL in the current study.

Fatigue Tests of Main Rotor Gearboxes

The manufacturer had conducted fatigue tests on a sample of Sea King MRGB's at a fatigue test power of 3720 hp (1860 hp per input drive); a nominal power of 150 hp was extracted through the tail rotor takeoff gear train.

For each fatigue test result on each gear, a value of P_0 was calculated from the data pair, P and N , using Eq. (1). The mean of the values of P_0 from the individual fatigue tests for each gear, divided by the fatigue stress factor, gave the "safe" endurance limit P_{ES} , and the "safe" $P-N$ (or $T-N$) curve for that gear as

$$P = P_{ES}(1 + AN^{-C}) \quad (2a)$$

Table 2 Rate of cyclic loading of MRGB gears, at 100% N_R

| Gear | Rotational speed, rpm | Load cycles, s |
|-------------------------|-----------------------|----------------|
| Input spur pinion | 18,966 | 316.1 |
| Input spur gear | 8,100 | 135.0 |
| Input helical pinion | 8,100 | 135.0 |
| Input helical gear | 3,195 | 53.3 |
| Spiral bevel pinion | 3,195 | 53.3 |
| Spiral bevel crownwheel | 940 | 15.7 |
| Epicyclic ring gear | 0 | 16.9 |
| Epicyclic sun gear | 940 | 61.4 |
| Epicyclic planet pinion | — | 9.3 |
| Main rotor shaft | 203 | |

Table 3 Gear endurance limits

| Gear | Power, P_{ES} , hp | Torque T_{ES} , % |
|-------------------------|----------------------|---------------------|
| Input spur pinion | 1439 | 118.3 |
| Input spur gear | 1415 | 116.4 |
| Input helical pinion | 1413 | 116.2 |
| Input helical gear | 1390 | 114.3 |
| Spiral bevel pinion | 2551 | 104.9 |
| Spiral bevel crownwheel | 2458 | 101.1 |
| Epicyclic ring gear | 2381 | 97.9 |
| Epicyclic sun gear | 2481 | 102.0 |
| Epicyclic planet pinion | 2268 | 93.3 |

$$T = T_{ES}(1 + AN - C) \quad (2b)$$

The magnitude of the fatigue stress factor applied was such that the "safe" $P-N$ curve was about three standard deviations below the mean, which for a normal distribution corresponds to a probability of approximately 1 in 1000 that failure would occur at less than the estimated "safe" life. It was shown¹⁸ that the 47 values of P_0 calculated from the results of the Wessex tail rotor fatigue tests using Eq. (1) could be adequately represented by the normal distribution. Variations of the "safe" curve relationship of Eq. (2) can be applied, and one used by the manufacturer in the region of the endurance limit was applied in the current study.

Values of the endurance limits P_{ES} and T_{ES} established from the fatigue tests are listed for all gears in Table 3. These values, together with Eq. (2), define the "safe" $P-N$ and $T-N$ curves for each gear.

As there were no fatigue failures during the tests of the input spur pinion, input spur gear, input helical gear, epicyclic sun gear, or epicyclic planet pinion, the endurance limits derived earlier for these gears are very conservative, as the specimens had some unknown residual life remaining when replaced during the tests.

Selection of Gears for Fatigue Life Monitoring

Using the operational contingency ratings for the Sea King and the appropriate $T-N$ curve, the microlife fractions expended by the application of each of the contingency ratings for 1 s were calculated for all gears in the MRGB.

At the higher contingency rating in single-engine operation, the input spur pinion had the highest rate of fatigue damage accumulation, therefore, both the port and starboard pinions were selected for monitoring. The manufacturer had assessed that the helical gear has a finite life, therefore, it was selected for monitoring.

In twin-engine operation at the maximum total power of 2700 hp, 313 hp (or 11.6%) is absorbed by the tail rotor and auxiliary drive, leaving 88.4% to be transmitted by the epicyclic gears to the main rotor. Using the twin-engine contingency ratings, the spiral bevel pinion has the highest rate of

fatigue damage accumulation and was selected for monitoring.

Therefore, it was decided that the FLUI would monitor the fatigue life expenditure of:

Input spur pinion—port gear train
Input spur pinion—starboard gear train
Input helical gear
Spiral bevel pinion

Data Assembly and Verification

The postflight printout data, together with the FLUI electromechanical counter readings entered manually by the ground crew (Fig. 2), were sent regularly to ARL, where they were transferred to an appropriate database via a ground station computing facility prior to analysis.

The data for each FLUI were arranged in the following flight sequence.

$$1, 2, 3, \dots, i-1, i, i+1, \dots, n$$

Using the nomenclature of Fig. 2, the following relationships should apply for flight "i":

Gear fatigue life usage:

$$(GEAR 1)_i - (GEAR 1)_{i-1} = G1 \quad (3a)$$

$$(GEAR 2)_i - (GEAR 2)_{i-1} = G2 \quad (3b)$$

$$(GEAR 3)_i - (GEAR 3)_{i-1} = G3 \quad (3c)$$

$$(GEAR 4)_i - (GEAR 4)_{i-1} = G4 \quad (3d)$$

Total flying time:

$$(TFTIME)_i - (TFTIME)_{i-1} = \text{Total flying time (s)} \quad (4)$$

Cumulative torqueband times

$$\sum_{j=0}^9 \text{TOTL} - j = \text{Total flying time (s)} \quad (5)$$

From Eqs. (3) and (4), any error in the sequencing of flights could be readily detected and corrected. Errors in the manually entered data on the FLUI printout or arising during the transcription of all values to the database could be detected and corrected, and appropriate values for missing data could be inferred on most occasions. In cases where such an inference was not possible, that flight was discarded from the analysis; in this study, 15 flights (6% of total) were discarded.

Concurrently with the data collection, the performance of the FLUI was monitored, and minor changes to procedures and to the airborne software/hardware were progressively implemented.

Following the verification and editing of the collected data where appropriate, valid data were available for a total of 227 flights, encompassing 479 flying hours.

Grouping of Flights

Examination of the "sortie type" entered on the FLUI printout showed that there were seven distinct types of flying, representing 85% of the total flights. The remaining 15% of flights were associated with 17 flight codes, each of which pertained to up to five flights; these were allocated to a miscellaneous group.

Examination of the number of flights and flying time for each type of flying for each aircraft, and the total over both aircraft, indicated that both aircraft had been performing similar flight duties.

Rate of Fatigue Life Usage

The proportion of flights during which some fatigue life usage was indicated is a small proportion of the total, and the value of the microlife fraction accumulated is small.

In individual flights, some fatigue life usage was indicated for G1 and G3 or for G2 and G3 during single-engine operation, and also for G4 during twin-engine operation. In other flights, some fatigue life usage was indicated in either single or twin-engine operation, but not in both.

Table 4 lists the rate of fatigue life usage for the four gears monitored; data for the port input spur pinion have been quoted, as it had a higher rate of life usage than the starboard pinion.

The relative rates of life fraction usage for the remaining gears was estimated by defining idealized torque spectra for both single- and twin-engine operation based on the measured load spectrum data. Briefly, this involved assuming specific torque levels and assessing the time of application of each to produce the measured microlife expenditure on the monitored gears. The relative rates of life fraction expenditure were, within limits, insensitive to the actual torque levels assumed. The results of this assessment are listed in Table 4.

Predicted Safe Life of Gears in the MRGB

Based on the total flying time of 479 h, the predicted "safe" life in hours is given by

$$\text{Safe life} = 0.75 \times 10^6 / (\text{microlife fraction/h})$$

The summation of life fractions to 0.75 follows the procedure used by the manufacturer to allow for the variability of the fatigue damage summation limit with load sequence and the variability of the load spectra for nominally similar aircraft usage. An earlier program¹³ on the Wessex helicopter gave support for summing to 0.75, as far as the variability of the load spectra in that aircraft is concerned.

The predicted "safe" fatigue lives of all gears are listed in Table 4 and all exceed 100,000 h, which is many times the life-of-type of the RAN Sea King helicopters.

When using data from a sample of aircraft to extrapolate the "safe" fatigue lives to the other aircraft in the fleet, normally it is necessary to establish that the sortie mix flown by the test aircraft is representative of fleet usage. In view of the long "safe" fatigue lives predicted, this aspect has not been pursued.

It is concluded that, for practical purposes, the lives of the gears in the MRGB of the RAN Sea King are not limited by fatigue.

Assessment of the FLUI

The two FLUI systems installed in RAN Sea King aircraft are prototype units that have not been upgraded, except to a very minor extent, since they were commissioned in 1982.

The effect of absolute (or mean) torque measurement inaccuracy on estimated fatigue life expenditure has been examined in a previous report.¹¹ It was shown that a small measurement inaccuracy can give rise to a very significant increase in estimated fatigue life usage relative to that which would apply for a system without measurement error. The source of greatest inaccuracy usually arises in the helicopter's hydraulic torque sensing system, which is likely to have a maximum inaccuracy

Table 4 Predicted fatigue life of gears in MRGB

| Gear | Microlife fraction, h | Predicted gear life, h |
|-------------------------|-----------------------|------------------------|
| Input spur pinion | 5.97 | 126,000 |
| Input spur gear | 7.18 | 105,000 |
| Input helical pinion | 7.39 | 102,000 |
| Input helical gear | 5.17 | 145,000 |
| Spiral bevel pinion | 3.88 | 193,000 |
| Spiral bevel crownwheel | 2.26 | 332,000 |
| Epicyclic ring gear | 0.07 | Unlimited |
| Epicyclic sun gear | 0.00 | Unlimited |
| Epicyclic planet pinion | 0.62 | 1,210,000 |

somewhere in the range of 2–10%. Various approaches to the inaccuracy problem can be considered:

1) Ignore the in-flight torque measurement inaccuracy on the basis that the applied stress factor will provide an adequately conservative estimate of fatigue life expenditure.

2) Factor the "safe" life so that the increments of life usage are summed to a value that is less than 0.75 used in this analysis.

3) Increase the stress factor by an amount that reflects the worst-case measurement inaccuracy.

The net effect of torque measurement inaccuracy is that indicated fatigue lives (i.e., "safe" lives indicated by the in-flight monitoring equipment) will be reduced when conservative action is taken to maintain the worst-case probability of premature fatigue failure at better than 0.001. This would normally be reflected by an increase in maintenance costs. It is, therefore, desirable that helicopter manufacturers aim to improve the accuracy of the torque sensing systems. It has now become common practice for engine manufacturers to incorporate on-engine torque sensors, usually to measure shaft angular twist. It is claimed that these systems provide much better torque measurement accuracy than the off-engine hydraulic systems.

It has been shown¹¹ that any departures in gear rotational speed from the nominal value will only affect the indicated fatigue life usage by a proportional amount and can be ignored. The FLUI uses the rotational speed value of 103% rated speed when estimating fatigue life usage. The rotational speed variation expected for normal operation is about 4%.

Discussions with squadron personnel who have operated the FLUI since it was commissioned have clearly identified some changes that should be incorporated into a production version to improve data integrity and ease system maintainability. In particular, the use of a printer as an output device has provided some advantages in the prototype proving phase but would not be recommended for long-term operational use throughout an entire fleet of helicopters.

To a large extent, appropriate auxiliary ground recovery equipment used together with a robust cassette storage output device could provide operating personnel with a rapid summary of the transmission load data as for the printer and simplify maintainability.

One aspect of significant concern has been that of the integrity of the electromechanical counter data entered manually on the printouts (Fig. 2). Screening of the data can be very time-consuming, and results in the discarding of some of the data collected. For improved data integrity, it was concluded that the need for manual entry of data should be minimized.

In the longer term, it is considered that upgraded fatigue monitoring equipment should provide:

1) Changes to improve operator acceptability and maintainability.

2) Capability to allow the life usage and condition of other components within the helicopter rotating machinery to be monitored.

3) Upgrading of the system elements to reflect advances in component technology that have occurred since the prototype FLUI was developed.

4) Extended capability to include other functions, such as health monitoring.

5) Capability for technology transfer to other helicopters, such as Seahawk (to be acquired by the RAN).

It has been shown that, under normal operating conditions, the fatigue lives of gears in the Sea King main transmission system, under RAN operating conditions, exceed the life-of-type of the aircraft. The fatigue discard lives promulgated by the manufacturer for the main transmission system gears fall short of the life-of-type prediction, but are substantial. Long fatigue lives make it likely that the gears will be replaced for other reasons (e.g., surface pitting or wear) before the manufacturer's fatigue discard lives are reached.

For transmission systems in which the fatigue discard lives for the gears are relatively high, the life extension, which would

normally result if gears are replaced according to assessed damage (i.e., life usage) units, may not yield significant economic benefits. The FLUI concept, however, can be applied to any helicopter and, in general, has the potential for substantial reduction in maintenance costs. On the other hand, in cases where operators may have loading patterns that are more severe than those upon which the manufacturer estimates discard lives, the assessment of discard lives according to actual loads encountered during service should prevent the safety of operation being compromised.

Under "normal" operating conditions, as referred to earlier, pilots generally maintain the torque developed by each engine within the limits prescribed by the manufacturer for continuous operation. Occasionally, due to pilot error or a genuine emergency, these ratings may be exceeded for a certain period. Under such "abnormal" operating conditions, RAN pilots are required to report the level and duration of the overtorque. The nature of these rare unpremeditated incidents renders it very difficult for the pilot to accurately note the requisite information. Moreover, the transient nature of most overtorquing incidents can render the cockpit torquemeter readings suspect, even if they happen to be noted correctly, due to the somewhat sluggish response of these meters.

Various levels of gearbox inspection are recommended by the engineering authority if overtorquing of the gearbox is reported. For Sea King, it is current practice for the RAN to inform the engineering authority if

- 1) Twin-engine torque level exceeds 120% for any period; or
- 2) individual engine torque exceeds 150% for any period during single-engine operation.

On receipt of a full report on the incident and on any previous history of overtorquing, the engineering authority may recommend that the MRGB be returned to its U.K. premises for inspection, at considerable expense to the operator.

The ability of the FLUI to estimate fatigue life usage, and also to accurately measure the level and duration of the over-torque, makes it a most useful tool in assessing the seriousness of the overtorquing and could greatly reduce the likelihood of an overhaul being undertaken to "cover the uncertainties of the reporting of the incident." To capture data relevant to the occasional overtorquing incident, which is considered to be a most important element of the gear fatigue monitoring for Sea King, it is essential that a FLUI be installed in each aircraft to monitor individual gearboxes.

Substantial advantages, as outlined previously, can accrue from the use of a FLUI in each aircraft. However, there would be considerable reluctance on the part of operators to install such systems if they were designated "flight critical" and, thus, required that the helicopter be grounded if the system is not operational. To alleviate this problem, a conservative estimate of the gear fatigue life usage for the given flight or flights could be used to provide values to be added to cumulative fatigue life usage figures in lieu of the in-flight data missed while the system is unserviceable. The conservative estimate could be based on operational load data collected for the various sortie types or could be, say, set to four times the average life usage per hour (which may be readily calculated from indicated total fatigue life usage and total flying time) multiplied by flying time in hours.

Further Research

The gear fatigue data ($S-N$ or $T-N$ curve data) supplied by manufacturers are usually based on tests to failure of a number of "normal" gears. It is most important that inspection procedures be thorough to reduce the possibility of a faulty gear being installed. When new gears or gears that have been in service are inspected, it is desirable that such technologies as X-ray examination or microscopy be fully exploited to improve defect detection capability. However, there is still a possibility that a "rogue" gear with an internal material or manufacturing defect may pass inspection and result in an early failure. Such a case has been reported by McFadden⁶ in respect to an early

catastrophic failure of the input bevel pinion to the MRGB in a RAN Wessex helicopter. Vibration analysis techniques developed after the failure occurred clearly identified an abnormality in the gearbox from vibration records taken a considerable time before the failure occurred.

The "safe" remaining fatigue life of a faulty gear or its degree of "damage tolerance" is obviously a subject of great importance, but little research has been done in respect of helicopter MRGB's. The damage tolerance approach has been applied successfully to fixed-wing aircraft structural and engine components. It has been applied to helicopter rotor blades that can fairly readily be inspected for damage at regular intervals, and the blade replaced if a fault is detected. It is imperative in such cases that the inspection interval be such that there is negligible chance of a failure occurring even if the fault were overlooked during one inspection. Fail-safe principles, such as the provision of redundant load paths and the use of damage tolerant materials, are already being applied in the design of new-generation rotor blades and hubs. Damage tolerance needs to be considered right at the design stage, and, in this regard, the U.K. Civil Airworthiness Authority³ states: "A damage tolerant design with a vibration health monitoring Expert System to alert the necessary conventional inspection, with usage monitoring to adjust the repeat interval, is an appealing combination of approaches which is not unrealistic in the next decade."

The combination of vibration health monitoring techniques, such as those developed by McFadden et al.⁴⁻⁶ and of life usage monitoring techniques discussed in this report provides the best approach to helicopter MRGB monitoring in the near future.

Conclusions

1) Conservative estimates of tooth-bending fatigue life usage per operating hour for various sortie types have been made for the Royal Australian Navy (RAN) Sea King main transmission system gears under normal operating conditions.

2) Under normal operating conditions, the fatigue lives of RAN Sea King main transmission system gears exceed the life-of-type of aircraft by a large factor.

3) Fatigue damage to gears ahead of and including the torque summing gear is not likely to occur except during single-engine operation.

4) For twin-engine operation, fatigue damage occurs mainly during rare excursions beyond maximum continuous torque rating.

5) Operational load data gathered by the fatigue life usage indicating system provide the means whereby an operator can assess his/her own usage spectra and provide important data to the helicopter manufacturer for the design and lifting of components.

6) The fitting of fatigue life usage monitoring systems to each aircraft in the fleet has the potential advantages that:

a) individual gearboxes can be monitored, and the gear fatigue discard lives rated according to the damage or life usage units actually accrued;

b) the severity of, and fatigue life usage, resulting from rare overtorquing incidents can be readily assessed; and

c) the safety of operation is improved, and maintenance costs reduced.

7) There is scope for more research into the application of the damage tolerance approach to both the design and life estimation of helicopter transmission and other mechanical components.

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