TWELFTH EUROPEAN ROTORCRAFT FORUM

Paper No. 86

DEVELOPMENT OF A FLEXIBLE AND ECONOMIC HELICOPTER ENGINE MONITORING SYSTEM

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September 22-25, 1986

Garmisch Partenkirchen
Federal Republic of Germany

Deutsche Gesellschaft für Luft- und Raumfahrt e.v. (DGLR)
Godesberger Allee 70, D-5300 Bonn 2, F.R.G.

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ABSTRACT

In terms of fatigue life consumption the Royal Netherlands Navy (RNLN) is by now one of the leading operators of the Westland Lynx helicopter. Consequently, the RNLN feels a growing need to gain more insight into the Lynx fatigue loading environment. The topic of Lynx engine loading is subject of a RNLN funded NLR research programme aimed at investigating the possibility of continuous and automated monitoring of engine fatigue damage accumulation based on the Rolls-Royce Cyclic Life Control concept. A pilot flight test programme has been carried out, the results of which are being used for the development of a usable Lynx engine in-flight data processor. Such a device will provide valuable information on RNLN Lynx engine service loading and may be the basis of computerized Cyclic Life Control within the RNLN in future. This paper will generally describe major topics of the above programme.

1. INTRODUCTION

Since 1976 the Royal Netherlands Navy (RNLN) operates the Westland Lynx helicopter in a variety of roles. Operational demand since then, in ground- as well as in ship-based missions, has led to a high degree of utilization. As a consequence, the RNLN is by now one of the leading operators of the Lynx when it comes to fatigue life consumption. In connection with this the RNLN feels a growing need to increase its knowledge on Lynx usage or, more specifically, to gain more insight into fatigue loading characteristics of its airframe, rotor system and engines. The present report deals with the latter topic of Lynx GEM engine usage monitoring.

Traditional engine component life philosophy is based on the safe-life principle. The safe-life depends on the component material's fatigue resistance to LCF-cycles such as start/stop cycles, and is defined as the number of cycles at which, say, in 1 of every 1000 (identical) components a crack grows to a certain size [1] [2]. After this safe-life has been reached by the component it will be removed from service, regardless of the presence of a crack. Moreover, due to uncertainties in service loading estimations and in material fatigue behaviour the engine manufacturer will build in certain reduction factors to arrive at safe retirement lives, expressed in flying hours, at which components have to be withdrawn from service. Inherently, these retirement lives are based on "safe" loading assumptions (i.e. cycles per hour) that are generally more severe than actual loading encountered in service.

From the above it will be clear that engine usage monitoring can be advantageous. On one hand monitoring actual engine usage eliminates part of the earlier mentioned uncertainties, giving rise to less severe reduction factors to be included in the retirement life specifications. This means upgrading to longer retirement lives if expressed in engine cycles and, thus, cost savings. On the other hand it describes the actual engine service loading environment and may lead to indications of major life consuming events within the operator's usage. By using this kind of information the operator can change logistic-, flight- or maintenance-procedures to allow a more economical helicopter usage.

Since 1982 Lynx operators have been provided by Rolls-Royce with service Bulletins subjected to application of Cyclic Life Control for GEM engines. They specify lives between overhauls in terms of actually flown and factored engine cycles rather than flying hours, provided adequate in-flight cycle counting procedures are used. In order to check the potential of Cyclic Life Control for its GEM engines the RNLN is funding a NLR research programme. As a first phase within this programme flight tests have been carried out to investigate the possibility of flexible, economic and computerized in-flight engine cycle counting. For this purpose a 4-channel ad-hoc measuring system has been built. The results of these tests showed that, with the ad-hoc system, application of automated Cyclic Life Control using a concept of on- line cycle recognition followed by off-line damage calculation has proven to be technically feasible.

The research programme's second phase, that is currently being undertaken, aimes at improving both hardware (with respect of weight and size) and software (with respect of the data handling procedures). Whereas in the pilot programme the cycle consumption has been calculated on an off-line basis, it is preferable to calculate the damage on-line and, by doing so, making the instrumentation more usersfriendly. Also, some other procedures that are specified in the Service Bulletin are being modified in order to achieve enhanced accuracy.

In the following sections of this paper the major topics of the current programme are being discussed.

2. GEM ENGINE USAGE

The RNLN operates 22 Westland WG-13 Lynx helicopters in three different versions: the Lynx UH-14A, equipped with Rolls-Royce GEM2/Mk.1001 engines, having a maximum all-up weight of 9750 lbs and the Lynx types SH-14B and SH-14C powered by GEM4/Mk.1010 engines and having increased weight capacity of 10500 lbs. Since the Lynx is a twin-engine helicopter 44 out of a total number of 70 GEM engines are actually being installed. Main tasks performed by the RNLN are Search and Rescue, Anti Submarine Warfare, General Duties and Surface Recognition. The projected helicopter usage is 300 hours/year, the projected engine usage is 200 hours/year. Recently, an overall survey of GEM engine usage has been released by Rolls-Royce indicating the amount of flight hours accumulated by various Lynx operators. Some of it is shown in fig. 1. It has turned out that the RNLN is the largest non-British GEM2 user with only 10 engines installed. With respect to the GEM4 engine the RNLN is by far the fleet leader. With 34 engines installed it accounts for almost 50 percent of worldwide GEM4 usage.

As mentioned in Section 1 engine components are lifed items, in general. Once the fatigue limit has been reached by a component, it will be withdrawn and replaced by another (new) component. Specifications of retirement lives for several critical GEM engine parts of the RNLN are given below:

MODULE		CRITICAL PARTS	RETIREMENT LIVES [HOURS]	
			Mk.1001	Mk.1010
05	h.p. turbine	disc; front/rear seal	1800	1200
06	l.p. turbine	disc	5639	5639
07	free power turbine	disc	5000	5000

The modular built-up of the GEM engine is clearly illustrated in fig. 2, with Modules 05 and 07 (resp. h.p. spool/combustion and free power turbine) being the most complicated modules. The item lives given above are indicated as not final and are, according to the Service Bulletin [3], to be increased as testing and service experience permits.

The high degree of Lynx utilization has the consequence that fatigue limits are being reached frequently. As an illustration, until June 1986 already eleven Modules 05 were withdrawn from service and were sent to Rolls-Royce for overhaul. To underline the operator's effort in this respect, the average overhaul costs for a Module 05 are appr. $ 100,000 while average overhaul duration is 9 months. Then, it may be realized that any modification in fatigue life control procedures, either adopted or proposed by the engine manufacturer, is of the utmost importance to the engine operator. Herein lies the fact that the Rolls-Royce concept of Cyclic Life Control has initiated the current RNLN/NLR investigation.

3. LIFING PROCEDURE

At this point it is worthwile to discuss the traditional safe life calculation procedure. As seen in fig. 3, two branches can be distinguished. The left side of the figure illustrates that the material's capability to endure fatigue loading is investigated experimentally through either test specimens or full scale components. Normally, the number of zero-max-zero cycles is determined at which, statistically, in 1 of every 1000 components (here: discs) a crack develops with a size of 1/32 inch (≈ .75 mm). Due to inherent scatter in material behaviour a reduction factor is incorporated in the determination of a "safe" number of cycles to first crack, i.e. the safe life expressed in zero-max-zero cycles. Thus, the result of material testing is a safe life in cycles. It immediately follows that, if the exact number of cycles should be known all the time during service, fatigue life control is rather straightforward.

However, due to the fact that, normally, this cyclic usage is not known a certain relation between flight time and engine cyclic usage is assumed. Then, by logging engine flight hours only it is possible to keep track of fatigue damage accumulation. The latter is illustrated at the right side of fig. 3. In order to correlate engine cycles with flight hours it is necessary that certain assumptions are made, namely:

- a description of operational usage by a limited number of different mission types,
- the establishment of a representative mission mix, and
- a derivation of a number of zero-max-zero cycles that is equivalent to one flying hour for each different mission type.

By combining the above features the average cyclic usage, i.e. the average number of engine cycles per general flight hour, can be determined. Since the operator's service usage may very well differ from the above assumptions, it is necessary to account for scatter in operator usage by incorporating an extra reduction factor. The result of this is a "safe" estimation of number of engine cycles flown per flight hour.

Thus, fatigue damage monitoring based on flight hours takes into account both scatter in material behaviour and usage variability. By monitoring engine cycles directly the latter is eliminated and the material's or component's fatigue potential can be used more effectively. The "economy" of the latter concept lies in the fact that uncertainties do not have to be accounted for. Based on this view Rolls-Royce has adopted the concept of Cyclic Life Control. This will be outlined in more detail below.

4. CYCLIC LIFE CONTROL

Rolls-Royce has issued GEM-engine Service Bulletin no. 5011 called: "Engine module and accessory lives and component retirement lives" [3].

In the service Bulletin information is given for the operator on how to establish the cyclic usage of fatigue critical rotating parts. If only regular flights are performed with sortie-patterns within narrow boundaries engine cycles can accurately be related to flights or flying hours and implementation of Cyclic Life Control will be rather straightforward. In all other cases, however, it will be necessary to count all cycles individually during each flight by continuously monitoring speed variations of the related engine components. This does not only apply to zero-max-zero cycles, but also to partial cycles within the major ones. In the Service Bulletin severity-(weighting-) factors are given for cycles of various magnitudes and mean levels in the form of min./max. (from/to) matrix-elements. In fig. 4 the so- called severity factor matrix for Module 05 (the gas generator) is reproduced from [3]. By holding these severity-factors against some established cycle content for a particular flight, it is possible to calculate the total amount of damage consumed during that flight.

In order to allow Cyclic Life Control the Service Bulletin contains procedure sheets for continuous hand-logging of engine speed variations by one of the cabin crew members. On a flight-by-flight basis the peak-through-peak sequences from these so-called Cyclic Record Sheets have to be combined with the severity factor matrices to determine the total damage. The signal N(h) is used to calculate the damage for both the gas generator HP and LP components, while N(f) gives the damage of the free power turbine.

However, continuous crew monitoring of speed using Cyclic Record Sheets on which each individual RPM-peak and -trough has to be read from the instrument's panel is not suitable. Hand-logging cannot be accurate and reliable. Furthermore, it will even be impossible under most operational conditions when crew workload is already high. The only practical way to implement Cyclic Life Control, in the opinion of the authors, is by automated data-acquisition and data-processing with a minimized amount of post-processing. The current RNLN/NLR programme is aiming at the development of adequate instrumentation and data-handling procedures.

5. RNLN/NLR PROGRAMME

Cyclic Life Control enables the operator to check life consumption in a more sophisticated way than is possible on the basis of flying hours only. On the other hand, it needs a reliable procedure to assess the cyclic engine usage on a flight by flight basis. Lit. [3] presents a simple means of storage of peaks and troughs of the RPM-history, to be made by hand by a member of the crew during the flight. Afterwards, these data are to be analysed in order to count its cyclic content. By multiplication with certain severity factors the final number of cycles flown is available. However, for reasons mentioned earlier it must be concluded that this data handling procedure by hand is not attractive. Recent electronic developments provide means to do the same in a far more economical, reliable and accurate way. Since the present application is not very different from other widely used data-processing procedures on, for instance, straingauge or accelerometer measurements, standard hardware and software is readily available or can be adapted easily.

In fig. 5 the various elements of the current research programme are shown. The steps that have to be taken to work out the possibility of automated Cyclic Life Control contain a loop in which the necessary instrumentation has to be developed, together with adequate data-handling procedures. After having optimized these steps the result is an instrumentation system that, following installation and implementation in one Lynx, will produce valuable information on typical engine loading. This may lead to ways in which a higher engine utility can be achieved. It can not yet be decided whether optimum application of Cyclic Life Control requires fleet fit instrumentation. A cost/profit analysis, incorporating also factors such as current and projected engine manufacturer's research effort and the operator's ability to handle extended instrumentation, must point that out. These topics, however, lie outside the scope of this report. The following sections will deal with the abovementioned instrumentation and procedure development-loop of the past pilot programme and the flight test programme following shortly.

5.1. Instrumentation

The NLR has ample experience with measuring and processing data from various sources such as aircraft, wind turbines and ships. Traditionally, the signal under consideration is sampled and stored on location on magnetic tape, and further data-handling occurres in the central NLR computer on an off-line basis. Only recently it has become possible to short-circuit some steps, i.e. to perform most of the data-reduction during the measurement itself. A powerful tool to do so is realtime rainflow counting with the results stored in a Markov-matrix. At the end of a test, all possible information concerning the signal's fatigue damage content can be determinded from the matrix. For instance, by performing specific walks through the matrix it is possible to derive peak- and trough-counting, range-pair counting and positive level cross counting results.

In order to apply Cyclic Life Control on this basis it is necessary to read from such a Markov-matrix the significant cycles, i.e. the cycles that are specified in the Service Bulletin severity factor matrices, with non-zero damage. Based on the above Markov-matrix concept a West-German measurement system, called MAS-system, has been developed which was expected to be suitable for the present purpose. It consist of a relatively light and small (appr. 2 kg, 100 x 110 x 220 mm) measuring device, called MAS-Box, which performs on-line data-processing in 12-bit resolution on any voltage signal (to be precise: 12 bit A/D conversion; 8 bit SPV; 6 bit RF). The kind of data-processing is software-based and may be freely developed by the user in assembler or machine-code. In connection with this in-flight data-processor a portable ground station, called MAS-Terminal, is used to load the data-handling software into the processor and to down-load or further process reduced data. This terminal makes use of a microcomputer that may be freely programmed in the system's Basic, either to modify or extend existing system-software or to develop completely new data-processing features.

Since the MAS-system is built up on a modular basis, with each module having a capacity of two channels, it is possible to monitor simultaneously both the Gas Generator speed N(h) and the Free Power Turbine speed N(f) for the two engines by using a 2-module MAS-system. In fig. 6 the complete instrumentation system, as used for the pilot programme, is shown. It consisted of a 2-module MAS-Box, a NLR frequency-to-voltage conversion box and a signal filtering box built together on an aluminium housed frame of size 470 x 420 x 260 mm. Due to the additional hardware necessary for this ad-hoc system the total weight increased from appr. 2 kg for the actual MAS- Box to 15.1 kg for the complete unit. The system was installed in a Lynx helicopter on the place of the sonar operator instruments rack, that had been removed for this purpose. As power supply the 115 V/400 Hz on-board system was used. A detailed description of the instrumentation system is given in [4]. For off- line post-processing the MAS-Terminal was used, also shown on fig. 6. Provisions had been made to transfer data from this handheld terminal into the NLR mainframe computer, a CDC Cyber 180-855. This was necessary to validate in an independent way the various data-handling actions of the flight-test instrumentation system.

5.2. Data handling procedures

Cyclic Life Control means calculation of damage consumed per flight. This damage is derived from cycles that are recognized within the RPM-signals. For the pilot programme two different approaches have been followed with respect to cycle recognition and subsequent fatigue damage calculation, see fig. 7:

1. - on line peak/valley search within the RPM data of the various signals and storage of this sequential peak/valley (SPV) sequence together with time marks in the MAS-Box memory
   - off-line down-loading procedure of the complete SPV-sequences to the Cyber computer
   - off-line calculation of fatigue life consumption using standard NLR rainflow analysis software combined with Rolls-Royce Service Bulletin severity factor matrices using the central Cyber.

2. - on-line determination of the cyclic content within the RPM data employing directly the MAS-system's rainflow counting software option and storage of cycles in (half) a 64 x 64 Markov "from-to" matrix in MAS-memory
   - off-line calculation of fatigue life consumption, using the MAS-Terminal with its built-in Service Bulletin severity factor matrices.

The reason for carrying out both procedures was to perform an independent check on MAS-capabilities by comparing its calculated damage after a flight with the result obtained through processing on the mainframe computer. By doing so, the accurate performance of the MAS-system could be validated.

Primary goal of the pilot programme was to investigate the possibility of simple and economic Cyclic Life Control by keeping track of actual engine cycles and by calculating associated fatigue life consumption from it. In a separate report [5] the procedures are described for the calculation of the number of reference cycles consumed during each flight.

Maximum simplicity was achieved by monitoring rotational speed through tapping off the speed indicator input signals (coming from tachometer generators) which are distributed to the flight instruments panel in the cockpit. By doing so the signals had to undergo a number of conversion steps before they were processed. Instrumentation was done this way to have the least possible impact on the existing helicopter electronics system, easing approval of test modification.

In short, the conversion steps were:

1. from [%RPM] to [Hz]: the frequency of the generator output voltage is directly proportional to the speed at which the engine component is driven. Thus, a change in rotational speed causes a variation in frequency output.

2. from [Hz] to [Volt]: the MAS-system is developed to monitor continuously voltage-time histories. In order to evaluate RPM data through tachometer generator frequency output it is necessary to convert this frequency signal into a voltage signal. For this purpose the NLR has built an electronics rack that not only converts the signal but also conditions the frequency-to-voltage step for optimum accuracy. A ratio of one MAS matrix class to 2.5 %RPM has been chosen [5].

3. from [Volt] to [MAS-class]: with normal parameter settings the MAS system classifies a voltage signal between class 1 and class 64 for voltage levels of resp. -10 V and 10 V. Together with the optimized frequency-to-voltage step, giving a final voltage range from -8 V (0 %RMP) to 6 V (110 %RPM), this results in a MAS class range varying between appr. 7 and 50 [6].

It must be realized that the procedures described above were not intended for implementation in the final instrumentation system. During the pilot programme the aim was to investigate the feasibility of the proposed approach of automated Cyclic Life Control by means of the MAS-system. In the present stage the MAS-Box is being modified to directly monitor frequency output for classification by the user's software. Also, the on-line capability is extended with the damage calculation, see also section 5.4.

5.3. Flight tests

The pilot programme comprised three test flights during which the signals N(h) and N(f) were automatically monitored in the way described earlier. The results of the flight trials are illustrated by means of the port engine N(h)-time history of flight no. 3, see fig. 8. Since time indications were stored with the momentary peaks and troughs and also detailed flight-event descriptions were available, it was possible to allocate these various events very precisely to the RPM-time traces. Some of the major events are pointed out in fig. 8. The results of the damage calculation is given in fig. 9. The bottom curve is the same as shown in fig. 8 and serves as a reference. The damage accumulation, based on the gas generator severity factor matrix of fig. 4, is shown as it builds up during the flight. In combination with the rainflow counting algorithm the severity factor matrix indicates four moments of significant damage accumulation, see points (A), (B), (C) and (D). In fact, there are only three moments during which fatigue damage increases during flight because damage step (D) represents the zero-max-zero cycle and is found by definition at the end of each flight. Due to the roughness of the severity factor matrix, with resolution of only 9 x 6, only very heavy engine cycles are associated with certain damage while, at the same time, the non-zero damage (weighting) factors are rather large in order to account for neglected cycles of smaller size. From fig. 9 it can be read also that, using the Cyber computer for data- analysis and using the severity factor matrix of fig. 4 for cycle weighting, the final total damage for the port-engine Module 05 (gas generator) accumulated to 1.40 cycles during flight no. 3. The other method, based on the MAS-system only, also gave a total damage of 1.40 cycles. This proved reliable and accurate performance of the chosen instrumentation. Based on the experience gained during the pilot programme flight test it was decided to proceed the programme with the current equipment. In order to arrive at a more autonomous and sophisticated performance of the instrumentation system certain modifications of the ad-hoc instrumentation system should be implemented, however.

5.4. Refined damage calculation

As outlined before, the procedure during the ad-hoc tests consisted of on-line rainflow counting with storage of cycles in a 64 x 64 MAS-matrix, followed by off-line damage calculation by multiplying each non-zero matrix element with certain severity (weighing) factors as specified in a Service Bulletin severity factor matrix of size 9 x 6. This procedure proved valuable for investigating the feasibility of automated Cyclic Life Control but it needs to be improved for actual developing standard procedures for it. In particular, this applies to two different features, i.e. the roughness of the Service Bulletin severity factor matrix and the extent to which on-line data-processing can be done in-flight. The various options are illustrated in fig. 10 and will be discussed below.

With respect to the Service Bulletin severity factor matrices it must be realized that they have been established on the basis of material test data. By weighting each individual cycle, taking into account its minimum and maximum load level, matrices with rather low resolution have been determined for publication in the Rolls-Royce Service Bulletin on Cyclic Life Control. As shown in fig. 9 this results in a somewhat rough damage calculation per load cycle. It will be clear that, given the fact that load cycles are being recognised in a computerised way, this damage calculation procedure suffers from unnecessary inaccuracy. Highest accuracy will be achieved by calculation fatigue damage for each individual load cycle from a relation with the following format:

$$D_c = F(N_{max}, N_{min})$$

where D_c is the damage per cycle and N_{max} and N_{min} are the maximum and minimum RPM-levels of the cycle under consideration. Such a relation has been made available by Rolls-Royce and could have been installed in the MAS-system's software for a direct off-line damage calculation, see lower left side of fig. 10. Since sequential peak/valley classification works with 256 different classes (8-bit resolution) an accuracy of about 0.4 percent will be achieved in this procedure.

It was decided to optimize the data-handling process in a way affecting both the resolution and the system's on-line capability at the same time. The instrumentation now being developed is capable of calculating the damage within the in-flight MAS-Box on-line, without the need to down-load the cyclic content first and to calculate the damage lateron with the ground-based MAS-Terminal. Also, the planned system configuration is aiming at minimum costs meaning that on-line calculation will not be done using a given damage formula considering each precise maximum and minimum RPM-level absolutely. Instead, new severity factor matrices will be installed specifying the weighting of individual cycles with far more resolution than the original ones. Based on the damage formula new 64 x 64 matrices have been generated that easily fit in the system's memory. After on-line recognition of a cycle it's peak and valley are rounded off to the nearest class of the new 64 x 64 severity factor matrix and are, or are not, associated with a certain damage fraction, see lower right side of fig. 10. By doing so, optimum performance will be achieved in relation to complexity, accuracy and cost-effectiveness.

The differences between the three damage calculation procedures are shown clearly in fig. 11. Using the Cyber computer the damage accumulation for the three different procedures shown in fig. 10 have been plotted in the same graph. The port engine damage accumulation according to the Service Bulletin data is indicated as (1) and is the same as shown in fig. 9. After having implemented the stress formula issued by Rolls-Royce a damage growth is found as given by curve (3). Clearly, the damage accumulates more smoothly than (1), while the total damage found is far less severe: 0.88 instead of 1.40 cycles. Obviously, the procedure proposed in the Service Bulletin is rather conservative. Also, a simulation of the MAS- Box performance has been carried out on the Cyber in order to indicate the projected MAS-system's operation in comparison with the other two methods. The MAS procedure, indicated by (2), shows good agreement with the theoretical calculation method and is, deliberately, kept slightly at the conservative side. This has been done by rounding off each RPM-peak and- trough to its associated class maximum instead of its class mean in the MAS damage matrix. The total amount of damage accumulated with the MAS-system is 0.98 cycles. Compared to the theoretical damage the Service Bulletin overestimates it some 60 percent, whereas for the MAS-procedure this is about 10 percent. Based on the above evaluation it is expected very worthwile to continue the amount research programme. It may improve the various GEM module lives between overhauls with some 40 percent, if automated Cyclic Life Control is being applied using the MAS-procedure instead of the proposed Service Bulletin procedure.

5.5. RNLN automated Cyclic Life Control

The way automated Cyclic Life Control is projected within the RNLN is illustrated in figs. 12 and 13. In the first instance one Lynx helicopter will be equipped with a 4-channel MAS-Box within the first half of 1987. This instrumentation will be fully autonomous and will monitor both N(h) and N(f) for port and starboard engine. During flight the box will search for reversal points within the signals, it will perform a rainflow analysis on these peak/valley sequences and it will determine the damage that is to be associated with each separate RPM speed cycle by considering built-in severity factor matrices. The damage accumulated per flight will be stored, as well as the total amount of damage accumulated from initial installation of the instrumentation. In order to have the possibility of a detailed check on any unreliable flight result the sequential peaks and valleys will be stored also. By doing so some data handling can be done afterwards, i.e. elimination of bad data, small modifications of measured values, etc.

After having gained experience with this system and in particular with its inherent data-handling procedures it will be decided how to proceed with respect to fleet-wide application of Cyclic Life Control. In any case, very valuable information on RNLN Lynx engine usage will be generated by the instrumentation system by then.

6. SUMMARY

The RNLN and NLR are developing a relatively small and economic Lynx GEM engine monitoring system intended to control in-flight LCF consumption. In this paper the results of a pilot programme have been discussed giving rise to a set of hardware and software specifications for use in the development of an 2^{nd}-phase instrumentation system. By the end of 1987 this system will have gathered ample data on operational RNLN Lynx GEM usage. This will not only help the RNLN in operating the GEM engine in a more economical way but it may be the onset of fully automated Cyclic Life Control within the RNLN.

7. REFERENCES

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ENGINE TYPE	OPERATOR	TOTAL HOURS	PERC.
GEM 2/Mk. 1001	ALL NL NAVY	443002 27480	100.0 6.2
GEM 4/Mk. 1010	ALL NL NAVY	79063 37768	100.0 47.8

(STATUS JULY 1986)

Fig. 1 GEM engine usage

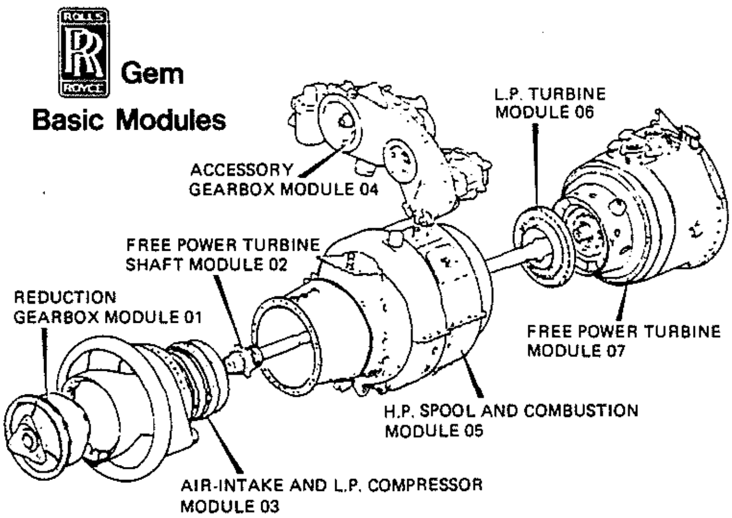


Fig. 2 The GEM engine

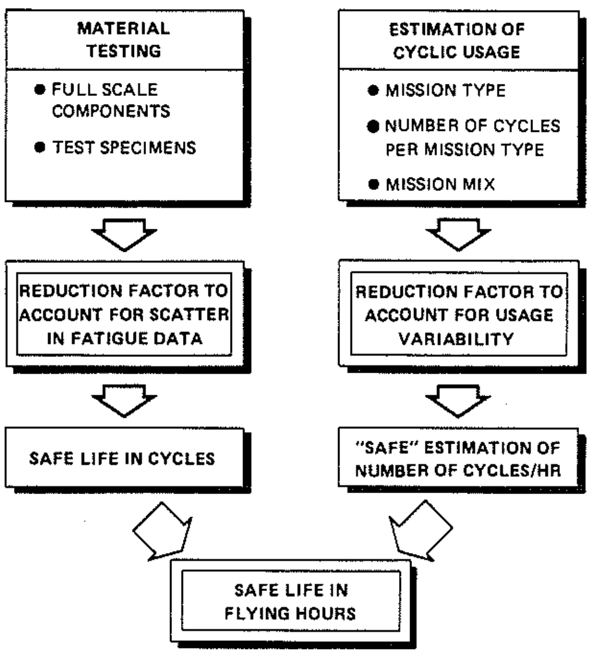
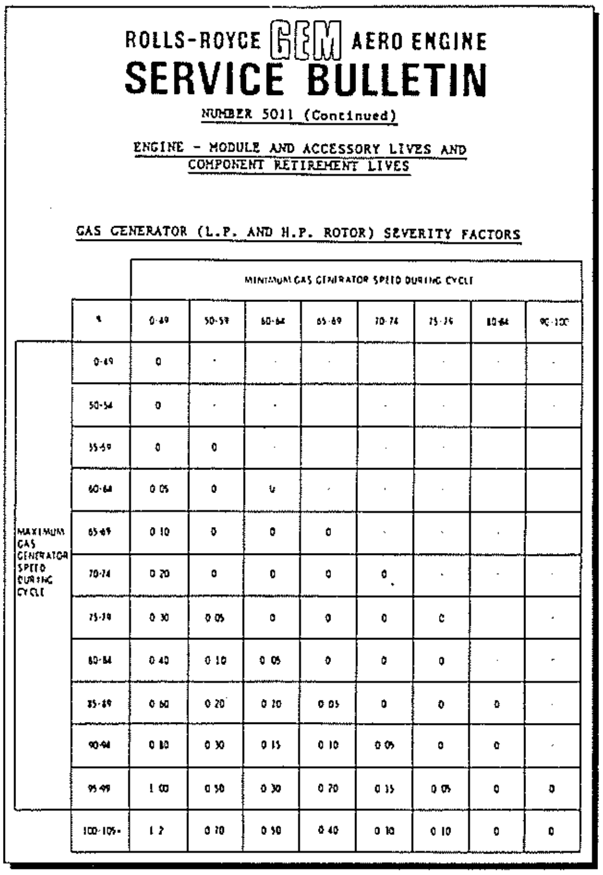


Fig. 3 Engine component lifing procedure



ROLLS-ROYCE GEM AERO ENGINE

SERVICE BULLETIN

NUMBER 5011 (Continued)

ENGINE - MODULE AND ACCESSORY LIVES AND COMPONENT RETIREMENT LIVES

GAS GENERATOR (L.P. AND H.P. ROTOR) SEVERITY FACTORS

		MINIMUM GAS GENERATOR SPEED DURING CYCLE							
	%	0-49	50-59	60-64	65-69	70-74	75-79	80-84	90-100
MAXIMUM GAS GENERATOR SPEED DURING CYCLE	0-49	0							
	50-54	0							
	55-59	0	0						
	60-64	0.05	0	0					
	65-69	0.10	0	0	0				
	70-74	0.20	0	0	0	0			
	75-79	0.30	0.05	0	0	0	0		
	80-84	0.40	0.10	0.05	0	0	0		
	85-89	0.60	0.20	0.10	0.05	0	0	0	
	90-94	0.80	0.30	0.15	0.10	0.05	0	0	
	95-99	1.00	0.50	0.30	0.20	0.15	0.05	0	0
	100-105+	1.2	0.70	0.50	0.40	0.10	0.10	0	0

Fig. 4 Gas generator severity factor matrix [3]

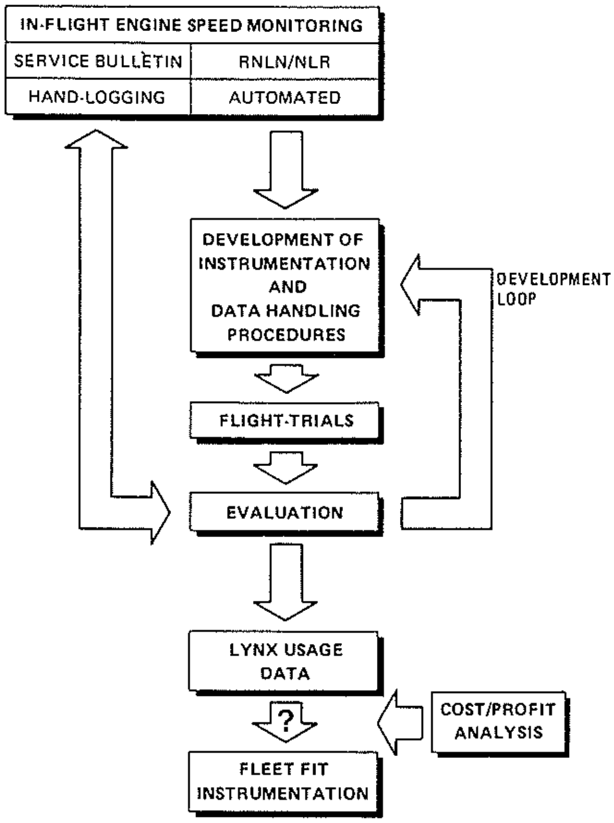


Fig. 5 RNLN cyclic life control development programme

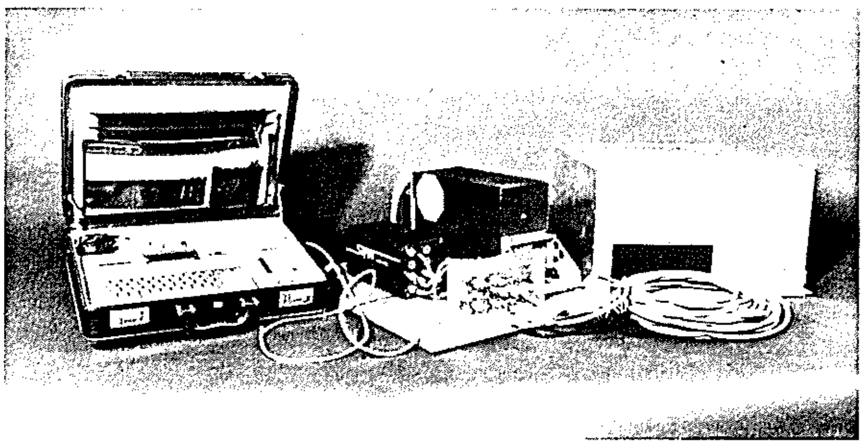


Fig. 6 Flight test instrumentation (pilot programme)

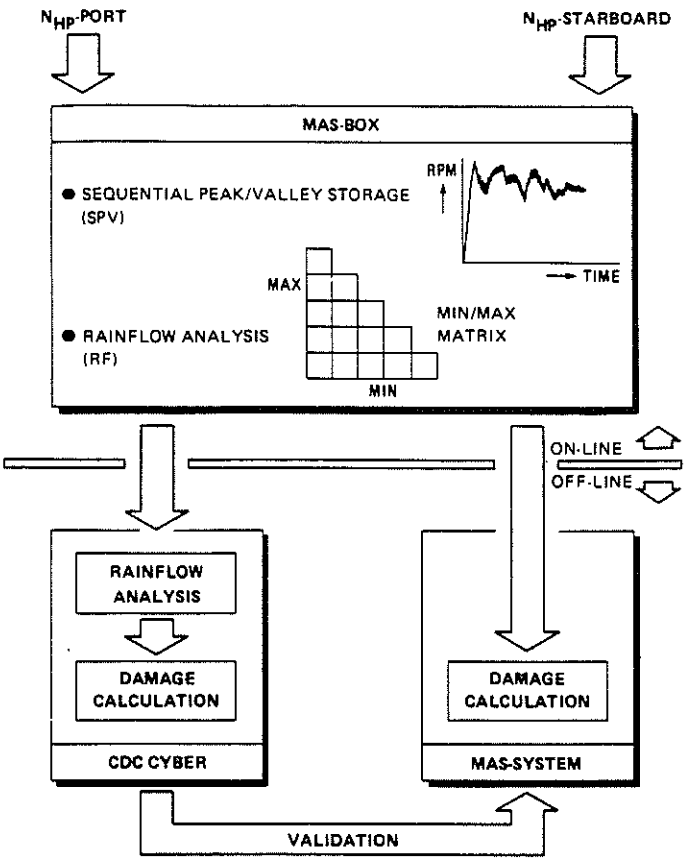


Fig. 7 Flight test procedures

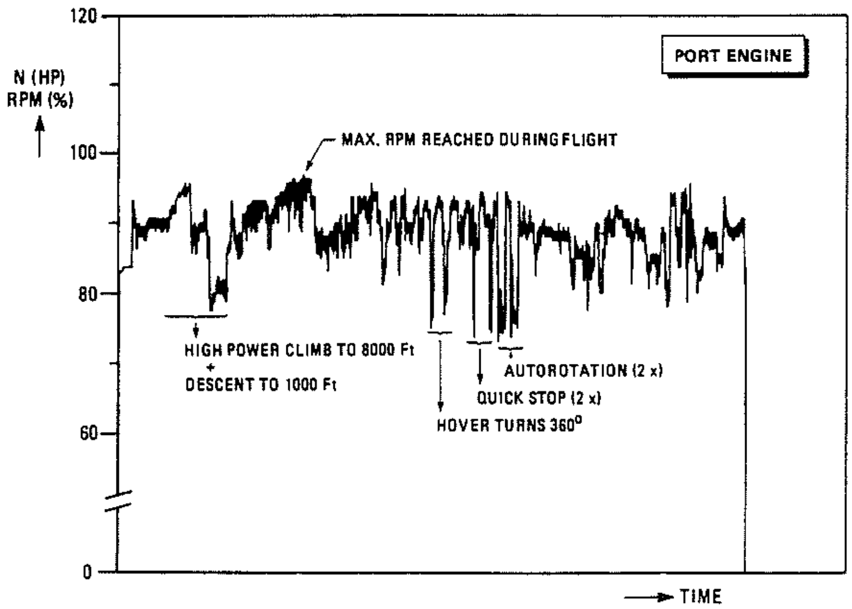


Fig. 8 RPM-time history port engine N (H) (flight no. 3)

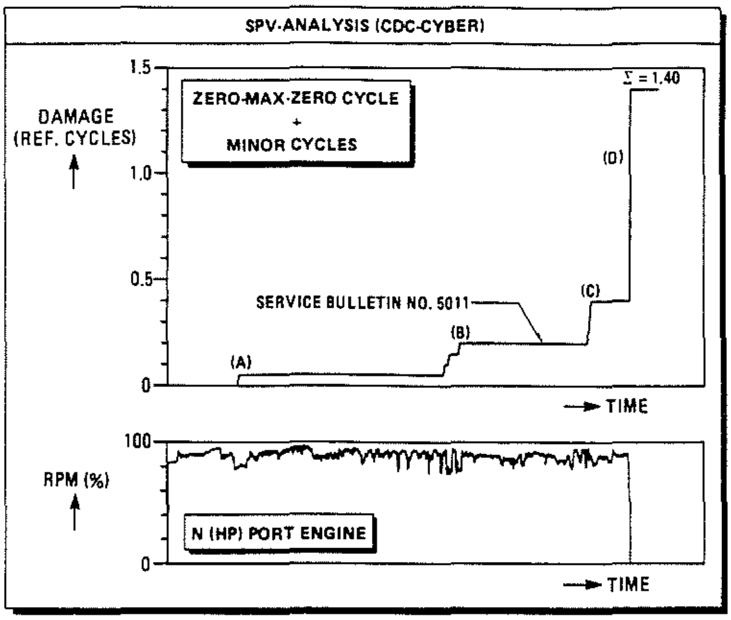


Fig. 9 Port engine damage accumulation during flight no. 3

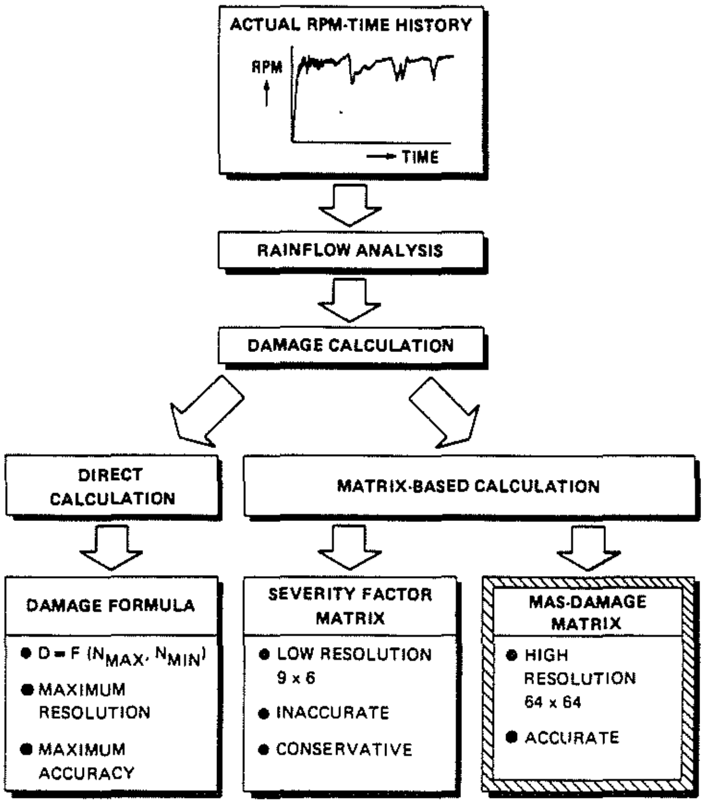


Fig. 10 Refined damage calculation

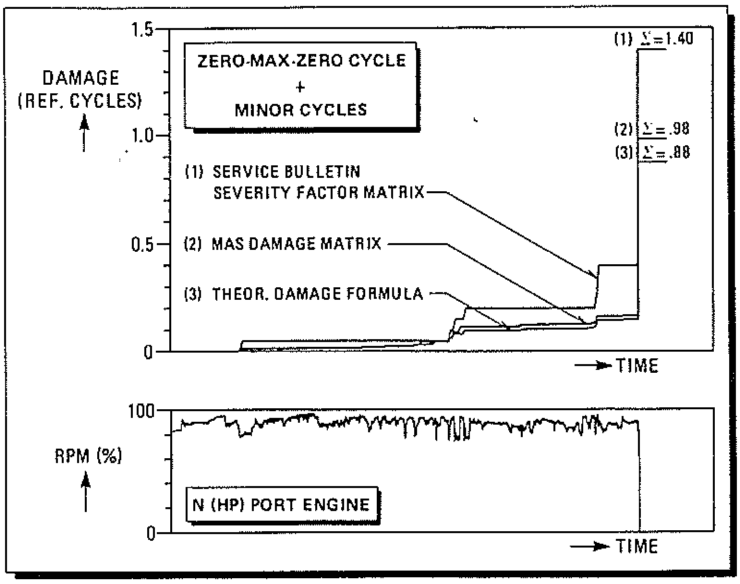


Fig. 11 Comparison of the various damage calculation procedures

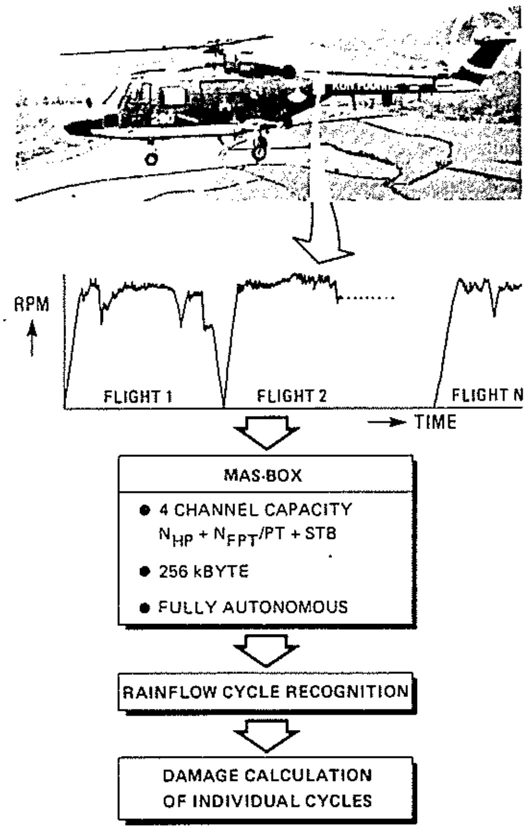


Fig. 12 Automated cyclic life control within the RNLN

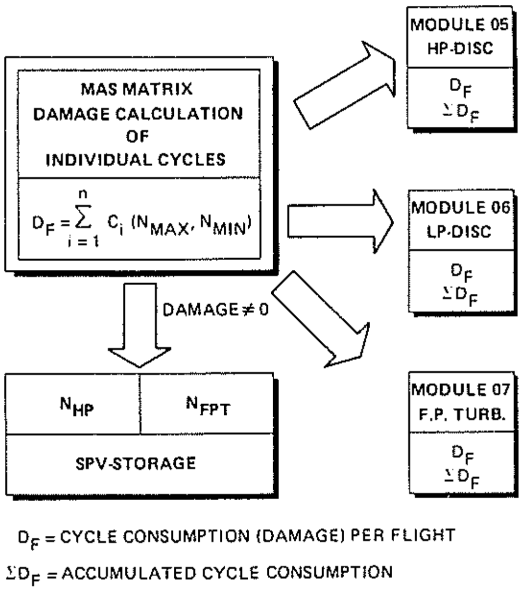


Fig. 13 MAS-box data handling procedures