RB199 Engine Oil System Failure Diagnostics by Comparison of Measured and Calculated Oil Consumption Using the OLMOS On-Board Monitoring System.

H. Pfoertner
H. Streifinger

MTU
Motoren- und Turbinen-Union Muenchen GmbH

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The oil consumption of military aircraft engines varies depending on the mission to be undertaken throughout a flight. In order to detect oil system related failures and to reduce the number of engine ground runs required to check the oil consumption, a mathematical model has been developed to calculate the expected oil consumption from available flight data. It has been implemented in the engine monitoring function of OLMOS. First flight test results and possible directions for the development of future systems are described.

Stoerungsdiagnose fuer das RB199-Oelsystem durch Vergleich zwischen gemessenen und mit dem OLMOS On-Board Ueberwachungssystem gerechneten Oelverbraeuchen.

Bedingt durch unterschiedliche Einsatzbedingungen verbrauchen die Triebwerke von Kampfflugzeugen pro Flug sehr unterschiedliche Schmieroelmengen. Um Fehler im Oelsystem zu erkennen und die Zahl von Triebwerks-Bodenlaeufen zur Ueberpruefung des Oelverbrauchs zu senken, wurde ein mathematisches Modell zur Berechnung des erwarteten Oelverbrauchs aus waehrend des Flugs verfuegbaren Messdaten aufgestellt. Dieses Modell wurde in die Triebwerks-Ueberwachungsfunktion von OLMOS integriert. Erste Ergebnisse aus Flugversuchen und Entwicklungsrichtungen fuer entsprechende zukuenftige Systeme werden erlaeutert.

Contents

	Page
1. Introduction	7
2. Engine Oil Consumption Diagnostics	7
2.1 Present Method	7
2.2 Improved OLMOS-based Method	7
3. Oil and Fuel System Description	8
3.1 RB199 Lubrication Oil System	8
3.2 Tornado/RB199 Fuel System	9
4. OLMOS Calculation Model	10
4.1 Breather Oil Loss	10
4.2 Oil Leakages of the External Gearbox and Breather Carbon Seals	10
4.3 Total Oil Loss	11
4.4 Mathematical Models for Different Algorithms	11
5. Implementation in OLMOS	12
5.1 Survey of On-Board Data Processing	12
5.2 Implementation of the Oil Consumption Algorithm	13
6. Test Results	14
6.1 Analysis of Recorded Flights by the German Navy	14
6.2 Flights with Prototype DAU1C Software at MBB	14
6.3 Flight Tests by the German Air Force	15
7. Improvements to the RB199 Oil Consumption Calculation	16
7.1 Scaling Factors derived from the OLMOS Field Evaluation	16
7.2 Sensitivity Analysis for Calculated Parameters	16
7.3 Additional Breather Rig Tests	17
7.4 Improved Mathematical Model	17

8. RB199 Oil Consumption Diagnostics with OLMOS 18
8.1 Presently Planned Usage 18
8.2 Improved Monitoring Procedure 18

9. Recommendations for New Engine Developments 19
9.1 Possible Applications 19
9.2 Required Engine Instrumentation 19
9.3 Required Rig and Engine Tests 19
9.4 Mathematical Model for New Engine Types 20

10. Conclusions 20

11. References 21

12. Figures 22

1. Introduction

High performance military aircraft (A/C), such as the Tornado, operate within a wide flight envelope. Typical missions include short high speed/low level flights as well as long high altitude ferry flights. It is known that the oil consumption (O/C) of the RB199 engine in the Tornado varies with flight Mach number, altitude, engine speed, engine oil temperature and, of course, with the flight time. Fig. 1 shows the large variations of the O/C at the maximum feed oil temperature and for maximum dry thrust. At lower oil temperatures and less than maximum dry engine thrust the O/C will not be as great.

Because of the large scatter and many influencing parameters, it is difficult to assess whether a high O/C during one mission is normal, indicates leaky or damaged external gearbox carbon seals or other oil system failures. If an excessive O/C were to remain undetected, there is the risk that the engine would consume the complete oil tank contents during one flight and consequently have to be shut down. If a high O/C in a preceeding flight, caused by the particular flight conditions, is misinterpreted to indicate an oil system fault, an unnecessary engine ground test run will have to be conducted. A reliable O/C diagnostics method is, therefore, important for flight safety as well as for economic reasons.

2. Engine Oil Consumption Diagnostics

2.1 Present Method

In the present method the flight time, Mach number and altitude of the previous flight have to be compared with a diagram similar to Fig. 1, if the total O/C during this flight exceeded 2.5 l/h. If the quantity of refilled oil is higher than the calculated maximum O/C (MOC), a special engine ground run has to be conducted. If the O/C during this test exceeds one litre per hour, the engine will have to be removed from the A/C for repair.

2.2 Improved OLMOS-based Method

MTU was asked by th German Air Force (GAF) to consider the possibility of calculating the engine O/C in the OLMOS (On-board Life usage MOnitoring

System) software with the aim to replace the inaccurate present method described above. Because the present method does not consider the effects of engine speed or engine oil temperature, it is very inaccurate, even if the flight Mach number and altitude were taken from the actual flight data. Consequently, a better method to calculate the O/C was required.

A correction method to take into account the engine speed can be based on measured data. Because for the RB199 there is only an oil "over-temperature" warning, the considerable effect of the oil temperature on the O/C requires either an expensive retrofit with an oil temperature probe or a calculation of this temperature. Fig. 2, which is based on rig test results, shows a rapidly growing O/C at breather oil temperatures above 175 deg C. To obtain a better understanding of this problem and the reasons which cause engine O/C, brief explanations of the RB199 oil system and of the Tornado/RB199 fuel system are required; these are described in the next section.

3. Oil and Fuel System Description

3.1 RB199 Lubrication Oil System

Fig. 3 shows a simplified oil system scheme for the MK103/MK105 variants of the RB199. The feed oil pump supplies oil from the oil tank to the bearing chambers and external gearbox to lubricate and cool the bearings and gears. Labyrinth seals separate the static bearing chamber walls from the rotating shafts. Air flows through these seals into the bearing cham- bers and prevents the lubrication oil from leaking into other parts of the engine. In the chambers, the oil and air partially mix. Most of the oil, and a part of the air, are delivered to the oil tank by the scavenge pumps. The largest share of the seal air, and a part of the oil, are vented to the breather, as well as air/oil from the tank and the gearbox.

The breather is a fast rotating centrifugal air/oil separator driven by the external gearbox. All vent air and oil enters the rotating breather at its outer diameter, from where the air flows to its centre and leaves the engine through the overboard pipe to the lower ambient pressure. Whilst most of the oil share is centrifuged out in the rotating breather and flows into the gearbox sump, oil vapour and very small oil droplets cannot be separated and are lost through the overboard pipe. This loss is a consequence of the oil system design and occurs also with new, perfectly healthy engines.

Because the pressure level inside the external gearbox and the breather is higher than the static ambient pressure, carbon seals are used to seal the output shafts and the breather overboard pipe. Any damage or wear of these seals will therefore cause oil leakages.

A fuel-cooled engine oil cooler (FCOC) is located in the pipe between the scavenge pump unit and the oil tank. It removes the heat from the oil, which has been generated by the bearings and gears and by heat flux into the bearing chambers. This heat-to-oil depends on the shaft speeds, the air pressures and temperatures in the engine and on the oil outlet temperature from the FCOC. The FCOC oil outlet temperature varies with the amount of heat-to-oil, the oil and fuel flow rates through the FCOC and with the fuel temperature at the cooler inlet.

3.2 Tornado/RB199 Fuel System

The fuel temperature at the FCOC inlet is determined by various parameters. Fig. 4 depicts the main relevant features of the complete fuel system for one of the engines. During engine operation, fuel from the A/C fuel tanks flows through pumps and A/C fuel-cooled oil coolers (for the hydraulic and secondary power systems) to the engine-FCOC, to the combustion chamber and to the afterburner. Several servo flows to the reheat control unit, for example the vapour core pump seal cooling flow, flow back to the first stage pump inlet. If the fuel temperature at the second stage pump exit exceeds a predetermined value, the fuel recirculation valve opens and increases the fuel flow through the coolers and pumps. This fuel is recirculated back to the fuel tanks. There is also a small continuous recirculation fuel flow from the recirculation change-over valve. Before it returns to the tank, the recirculation flow is cooled by an air cooled fuel cooler.

During ground stand-by operation with running auxiliary power unit (APU) and with shut down main engines, fuel flows through the A/C coolers and back to the fuel tanks (not shown in Fig. 4). At certain conditions, the fuel temperature in the A/C tanks increases slowly from the heat produced by the hydraulic and by the secondary power systems.

The fuel temperature at the engine-FCOC inlet is therefore determined by the tank fuel temperature prior to APU start, by the duration of APU ground operation, by the flight Mach number, altitude and ambient temperature (the latter heats or cools the fuel in the tanks as well as in the air cooled fuel cooler). The fuel is heated by the fuel pumps and by the oil coolers. The tanks are heated or cooled from the returning recirculation flow through the air cooled fuel cooler. The "history" of the mission therefore influences the engine-FCOC fuel inlet temperature and, via the FCOC, the engine oil temperature and O/C.

4. OLMOS Calculation Model

4.1 Breather Oil Loss

The breather oil loss is the sum of vapour and liquid (droplet) losses. The vapour oil loss through the breather depends on the vapour pressure of the oil, and therefore on the oil temperature as shown in Fig. 2. Further variables considered are the oil density, the breather pressure and overboard air flow. Oil droplets pass through the breather, if they are so small that their drag is higher than the centrifugal force acting on them. The liquid loss therefore varies with the breather rotational speed, breather pressure, overboard air flow and temperature-dependent oil density. Fig. 2 shows that at lower oil temperatures, the majority of the loss is due to the liquid oil.

Semi-empirical formulae, based on rig-test results and validated by bench engine tests, are used to calculate the breather losses. The effect of the rotational speed on the liquid loss has been neglected, because no test data were available when the model was used in conjunction with OLMOS. Fig. 5 shows the calculated breather oil temperature (Tobr) together with some important influencing parameters for a recorded Tornado flight for one engine. In Fig. 6, curve 1 shows calculated vapour loss, curve 2 shows calculated liquid loss for the mission of Fig. 5.

4.2 Oil Leakages of the External Gearbox and Breather Carbon Seals

Oil leakages through the gearbox and breather carbon seals are negligible for new engines, but constitute the majority of oil losses for engines with worn or damaged seals. The oil flow is calculated using a formula for a flow through a gap. A constant in the formula has been adjusted to give a calculated MOC (i.e. breather plus leakage loss) of 1 l/h, if the engine is operated at the conditions of the O/C engine ground test run. This is equal to the rejection limit described in section 2.1. The gearbox and ambient pressures as well as oil viscosity and density at the feed oil temperature are variables in the oil leak calculation. Curve 3 of Fig. 6 shows the calculated maximum leakage loss for the Fig. 5 flight.

4.3 Total Oil Loss

The total EOC is the time integral of the sum of curves 1 and 2, whereas MOC is EOC plus the time integral of curve 3.

The accuracy of oil refilling and of reading the refilled quantity is known to be about +- 0.5 litres. To increase the accuracy for the comparison between calculation and measurement, the calculated O/C have to be added and to be compared with the total quantity of refilled oil for a certain period of time. Errors from incomplete oil tank refilling will thus be corrected after some refillings and errors in the reading of the correct amount of refilled oil (over-estimations and under-estimations) should compensate after a certain number of refillings.

4.4 Mathematical Models for Different Algorithms

Investigations were carried out with the RB199 heat-to-oil computer program, which calculates the engine oil temperatures and the O/C with detailed physical models. The FCOC fuel inlet temperature was taken from computer simulations of the Tornado heat management system and from flight test results.

Due to the complexity of the mainframe heat-to-oil computer program it could not be used in the OLMOS system. Two simplified O/C algorithms were developed and their calculated O/C were compared with the results of the heat-to-oil computer program as well as with the present method using a diagram similar to Fig. 1. For both algorithms, simple empirical correlations to calculate the relevant oil temperatures were developed, including a formula for the transient, time dependent effect.

Algorithm 1 uses the breather formulae with calculated breather pressure, overboard air flow, oil vapour pressure and density as well as diagrams and a formula to derive the breather oil temperature. For this the effects of engine speed, Mach number, altitude and ambient temperatures are considered. Algorithm 2 uses diagrams similar to Fig. 1, but for different feed oil temperatures and with correction curves for the effects of engine speed, Mach number and altitude.

The feed oil temperature required to calculate the oil viscosity and density for the carbon seal leak is calculated with the same formula for both algorithms. The gearbox pressure is calculated in Algorithm 1 to derive the breather pressure.

A comparison of the calculation method using Fig. 1 with the results of the detailed heat-to-oil calculation revealed a mean difference of +- 0.7 l/h, while it was less than +- 0.2 l/h for the two more detailed algorithms. When the GAF placed a contract for the implementation of the O/C calculation into OLMOS, it was decided to use Algorithm 1 with the breather oil loss formulae, because it is more flexible and can be improved more easily.

5. Implementation in OLMOS

5.1 Survey of On-Board Data Processing

A survey of OLMOS is given in [1]. The on-board functions are performed within the DAU1C (Data Aquisition Unit). It collects and processes data from the A/C and the engines, sends data to the crash recorder and the maintenance recorder (MR) and performs the OLMOS functions using three microprocessors. CPU 1 monitors the aircraft structure and performs all data collection and transfer functions. CPU 2 and CPU 3 monitor the engines with identical software on both processors. A summary of the first version of the engine related monitoring functions is given in [2].

As a consequence of the introduction of the new engine variant MK105 for the ECR (Electronic Combat and Reconnaissance) Tornado, a comprehensive update of the DAU1C software was necessary to take account for the changed engine features. It includes a restructure and extension of the result data set as well as a revision of the data transfer and update logic.

5.2 Implementation of the Oil Consumption Algorithm

One part of the software update was the introduction of the O/C algorithm into the DAU1C. The first step was the conversion of the selected O/C algorithm into integer arithmetic. Based on the experience gained with the transformation of the life usage algorithms no significant loss of accuracy was introduced by the real to integer conversion.

The new code to be written was around 100 lines of Fortran. After translation into the C language and implementation into the microprocessor the code requires 3.2% of the total program space. The CPU time needed per call is 7 ms on the Motorola 68000 clocked with 10 MHz. It may be of some interest that the current version of the DAU1C engine monitoring software has a worst case CPU time of 140ms for a 500ms timestep, program space is less than 50% and RAM space is less than 60% of the available memory.

The O/C function is called at the same location and at the same rate (every 0.5s) as the calculation of gas temperatures and pressures needed as input for the computation of thermal stresses within the compressor and turbine discs. The additional effort to include the O/C algorithm into the life usage program was very limited. Only some intermediate results had to be made available to the calling program.

As a reprogramming of the on-board software can only be done by pulling computer boards out of the DAU with a consequential requalification of the system, some important parameters of the O/C algorithm have been incorporated in the monitoring control parameter set, which can be accessed and changed via the central logistic system.

The increments in O/C per 0.5s time step are of the order of magnitude between 0.02 and 1.5 grammes. The internal scaling for O/C is 2**24 per 1 kg of oil. Thus the accuracy of accumulation of O/C is 0.3%, even for the minimum increments. The accumulation of the different contributions to O/C (see Fig. 6) for one engine run is done on 32bit variables with a scaling of 2**24 per kg.

To summarize, it can be said that the numerical error introduced by the conversion of the O/C algorithm into its on-board version is negligible if compared to the errors introduced by the model assumptions. Thus the accumulation of EOC and MOC over several engine runs can be done with sufficient accuracy using two 16bit variables stored in the battery buffered RAM with increments of 1/16 litre.

To transfer the result of the O/C calculation to the HHT (Hand Held Terminal) some spare locations in the result data set were activated. To display these results to the maintenance personnel a reprogramming of the HHT software was necessary. The results transferred between DAU1C and HHT (MOC for the last 6 engine runs and accumulated EOC and MOC) have a scaling factor of 16 per litre.

In the current OLMOS version now being retrofitted at all German Tornado wings, the results of the O/C calculation can only be displayed at the HHT. The OGS (OLMOS ground station) does not display or store these results.

6. Test Results

6.1 Analysis of Recorded Flights by the German Navy

First flight tests were performed by the German Navy with two Tornado A/C. The flights were recorded with the MR and the data were sent to MTU together with the O/C sheets which contain the amounts of oil used to fill the oil tank after the flight. The recorded flights then were converted into the data format used by the mainframe OLMOS-reference computer program, and the O/C for those flights was calculated.

Results are available for six flights. The quotient (measured O/C)/EOC (QME for short) exhibited a large scatter between 0.3 and 2.16 for individual flights. The reason is assumed to be the inaccuracy of +-0.5 litres when refilling the oil tank. From these results it was concluded, that only the observation over a longer time period could lead to a validation of the proposed method.

6.2 Flights with Prototype DAU1C Software at MBB

During the development of the new version of the OLMOS system more than 70 flights with the prototype OLMOS equipment and the corresponding on-board software were performed on a fly-along basis in the German Flight Test Centre in Manching. A measured O/C was only available for a few of these flights. From the limited data available it could be seen that the calculated EOC was generally too high by a factor of approximately 2 (QME approximately 0.5).

In January 1991 seven consecutive flights with a total of 17 hours ERT (Engine Running Time) per engine were performed with a prototype ECR Tornado, which was equipped with MK103 engines and the latest version of the new OLMOS. For these flights very reliable O/C readings were also available. The quotients QME were in the range from 0.17 to 1.33 for single flights. The quotient (total measured O/C for 7 flights / accumulated EOC) was 0.53 and was exactly equal for both engines.

6.3 Flight Tests by the German Air Force

More than 500 flights were performed with eight Tornado A/C at the GAF base Jever (JaboG 38 "F"). These A/C (five with MK105 engines, three with MK101) were equipped with different development versions of the OLMOS, but were otherwise operated in the same manner as all other A/C of the wing. A comparison of calculated EOC and MOC with measured O/C was performed over a period of four months. Data were collected for an accumulated EFT (Engine Flight Time) of 790 hours. The longest continuously monitored period for one engine was 84 hours EFT.

A record of O/C was set up for each A/C. The data displayed at the HHT after readout (normally performed in the evening after the flights) were entered in the record together with the measured O/C written down in the A/C log book. The calculated EOC was always higher than the measured O/C. Fig. 7 shows a typical result for a MK105 engine.

For eight MK105 engines QME was between 0.50 and 0.41 with an EFT-weighted mean of 0.47. Two MK105 engines (both in the same A/C) had a sigificantly higher O/C with quotients of 0.75 and 0.72, the reason for which is not understood so far.

The five MK101 engines investigated (data were corrupted for one engine) had a lower O/C with QME between 0.45 and 0.29 with an EFT-weighted mean of 0.37. The reason for the different behaviour of MK101 and MK105 engines could be oil system differences (MK101 engines have a cyclone separator for the vent pipes which reduces the oil flow to and the oil temperature in the breather), which are presently not considered in the OLMOS O/C function.

7. Improvements to the RB199 Oil Consumption Calculation

7.1 Scaling Factors derived from the OLMOS Field Evaluation

As a first consequence of the flight test results a simple adaptation of the calculation can be achieved by scaling down the vapour loss, liquid loss and seal leakage by fixed factors. No change of on-board software, which would not be accepted by the customer anyhow, is necessary since the adaptation can be done by a change of the monitoring control parameter set. Fig. 7 shows that using a scaling factor of 0.51 for the EOC (which was derived from the MK105 results by taking the arithmetic mean of all observed quotients) produces a much better correspondence between calculated EOC and measured O/C than before. Nevertheless, possible reasons for the large over-estimation of the O/C have been investigated as well.

7.2 Sensitivity Analysis for Calculated Parameters

A detailed consideration of the data from the in-service evaluation revealed that, in most cases with long flight times between oil refillings, the actual O/C per flight hour was relatively low and significantly less than the EOC. For short flight times between oil tank refillings and relatively high actual O/C per flight hour, the EOC was approached and sometimes was even lower than the actual value. This is an indication that for short, high speed low-level flights the algorithm yields results which are more accurate than those for long lasting high altitude flights.

All rig tests, on which the breather oil loss formula is based, were conducted at sea level conditions and the altitude effect may have not been implemented correctly. Because of the heavy instrumentation of the test bed engines used to validate the formula, internal oil leakages could have caused additional losses which improved agreement with the EOC. Nevertheless, some engine tests indicated that the breather oil loss formula yields conservative values at high altitudes. However, because of the low O/C and measuring accuracy at these conditions, this could not be fully proven.

As discussed above, simplifications have been made in the calculation of the breather oil temperature, from which some inaccuracies could be expected due to different conditions from those of the flight-test results and calculations used for the development of Algorithm 1 (duration of APU ground running, Mach numbers and altitudes flown, lower ambient temperatures than in the flight tests and Tornado heat management calculations). Fig. 5 indicates, however, that for typical flight conditions of the GAF the breather temperatures are relatively low and, as shown in Figs. 2 and 6, the liquid breather loss share is far more important than the vapour loss. Errors in the calculated temperature have thus only a small influence on the O/C. For hot climate conditions the vapour loss share can be much higher, however.

7.3 <u>Additional Breather Rig Tests</u>

In order to provide data for an improved breather oil loss calculation model, a new series of rig tests was funded as part of the OLMOS project. Tests are planned with individual variations of the many parameters which could influence the breather oil loss. They include rotational speed (all previous tests were at maximum speed), ambient pressure (all previous tests were at sea level conditions), oil flow rate into the breather (all previous tests were with a constant oil flow rate), oil temperature and overboard air flow.

First test results indicate that the oil loss rises at lower breather speeds. The effect is of limited importance, because the absolute oil loss at low speed engine conditions is very small. There could be a considerable influence of the oil flow to the breather, which could also explain the lower than calculated O/C at high altitudes (less vent air/oil flow). The reduced O/C of MK101 engines, relative to the MK103/MK105 standard, could be caused by the reduced vent oil flow with the cyclone separator.

7.4 <u>Improved Mathematical Model</u>

After completion of the rig tests, an improved mathematical breather oil loss model can be developed with the additional parameters not available from the previous rig tests. No requirements for modifications to other parts of the model can be obtained from the available flight test data. Only when data for high ambient temperatures become available, the accuracy if the oil temperature algorithm could also be checked. Because Algorithm 1 with the breather formula was preferred to Algorithm 2 with breather oil loss diagrams, less effort will be required for the modifications.

8. RB199 Oil Consumption Diagnostics with OLMOS

8.1 Presently Planned Usage

After the adjustment of the monitoring control parameters and the retrofit of the new OLMOS software (including the O/C calculation) at the Tornado wings, a revision of the present procedure for the handling of high O/C is envisaged. The calculated MOC will then be used instead of the method described in section 2.1. An inquiry of the pilot about flight conditions is no longer needed. Readout of O/C data with the HHT will only be carried out upon request. The accounts showing accumulated EOC and MOC will only be used for verification purposes by industry.

8.2 Improved Monitoring Procedure

As already mentioned, a comparision of O/C data for single flights results in a large scatter of the quotient QME. A warning generation cannot be based on this quotient, therefore, without additional processing. In order to detect incipient failures before the MOC criterion is exceeded, and to avoid an excessive false alarm rate, the following method is proposed:

Calculated EOC is listed together with the measured O/C, as already performed in the Jever flight trials. The quotient QME is not only taken from the last single flight, but also includes the data of previous flights, so that a minimum ERT is used to calculate QME. Fig. 8 shows an example deduced from real O/C data, but with an assumed constant O/C per ERT and a fictitious oil leak occuring at 38 hours ERT. By choosing a suitable averaging time and corresponding warning limits a compromise between false alarm rate and warning delay has to be found. In this example the warning would be raised only 10 hours after the first occurence of the leak, which obviously is a consequence of the selected averaging time.

Carrying out the proposed trend analysis on a routine basis requires an automated procedure of O/C data gathering in a ground station computer. If all the data were available within a ground station, O/C trend analysis could be coupled with an automated oil system diagnosis, as it is described in the thesis of Willan [3].

9. Recommendations for New Engine Developments

9.1 Possible Applications

An oil consumption trend analysis as presented in this paper is of particular use for engines with large O/C variations due to their mission profiles, such as those used in high performance military A/C. If an oil temperature instrumentation is available, only additional software on-board the A/C and in an engine health monitoring ground station (for O/C trend graphics and for statistical calculations) is required. Because all important data are already recorded for many engine types used in civil airliners (oil temperature, gearbox and ambient pressures, oil tank contents), only an additional algorithm in the health monitoring computer would be required to perform the O/C monitoring function and trend analysis developed for OLMOS. If required, this could be performed even on-board.

9.2 Required Engine Instrumentation

To improve the calculation accuracy and simplify the algorithms for O/C calculations, the oil temperature, also used for oil over-temperature warnings, should be measured in new engine types and be applied in the breather loss formula. Other data required will normally be available anyway (ambient pressure, engine speed) or can be calculated relatively simply and accurately, if not measured (breather or external gearbox pressure). The overboard air flow can be calculated either from one of these pressures or from available engine pressures required also for the control system.

9.3 Required Rig and Engine Tests

In rig tests, the effects of rotational speed, oil temperature, ambient pressure, overboard air flow and oil flow to the breather should be varied independently to allow the development of an accurate breather oil loss formula. Altitude test facility engine runs will be required with sufficiently long running times at fixed conditions, in order to allow an accurate O/C measurement for the validation of the rig test based formula. Engines without significant internal or external oil leakages are required to avoid an over-estimation of the breather oil loss in the engine.

9.4 Mathematical Model for New Engine Types

A simple mathematical model could be used in an engine with sufficient instrumentation. Only the breather and carbon seal leakages as well as the overboard air flow, the oil flow to the breather, the oil density, viscosity and vapour pressure as well as the breather pressure (if not measured) would have to be calculated in a system with a recorded oil temperature. No effects from the fuel system and no heat-to-oil effects would have to be estimated and programmed. Scaling factors should be available similar to the OLMOS system in order to be able to consider in-service experience. The implementation into an existing health monitoring computer should pose no unexpected problems.

10. Conclusions

Proposed by the GAF, a system has been developed which will allow a better O/C monitoring for the detection of leaky gearbox seals and other oil system faults. Scaling factors for the breather and seal oil losses can be considered in order to allow changes from service experience. Because the RB199 has no measured oil or fuel temperature, simplified algorithms for an oil temperature calculation had to be developed. To avoid this problem with future applications in other engines, the provision of an oil temperature probe is proposed, as the minimal undertaking.

The implementation of the present O/C program into OLMOS showed only a small effect on the OLMOS computational time with no adverse effect on other functions of the system. Additional rig tests will allow to improve the breather oil loss formulae and should correct the high breather oil loss calculated at present. The improved formulae could be implemented in a future OLMOS software update. Together with the proposed trend analysis, the OLMOS O/C calculation should prove to be a useful tool for the detection of leaky engines and, possibly, even for the selection of Tornado A/C for missions with expected high O/C (long ferry flights, etc.).

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12. Figures

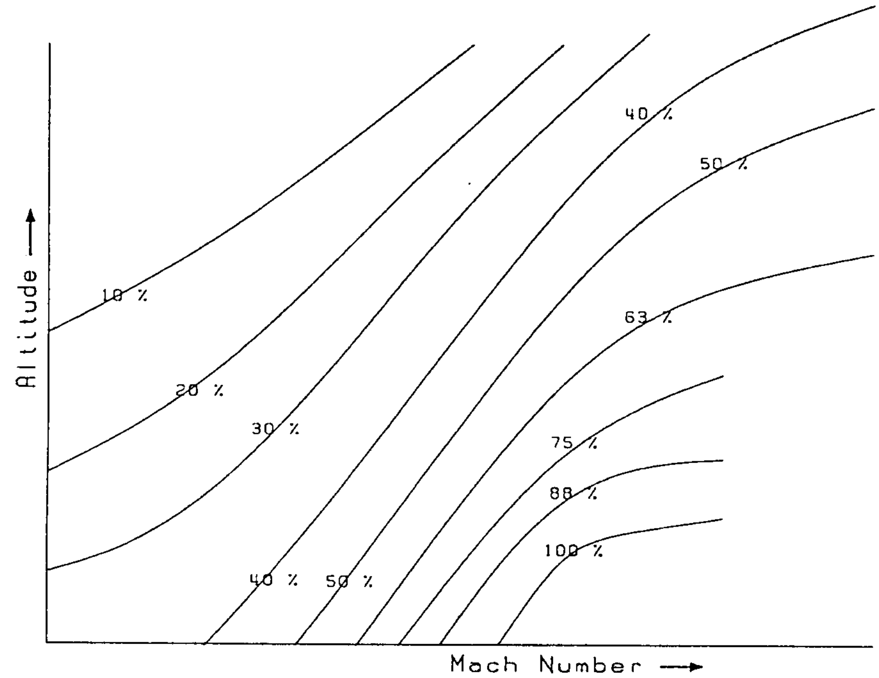

Fig. 1 Maximum Oil Consumption at Maximum Dry Thrust

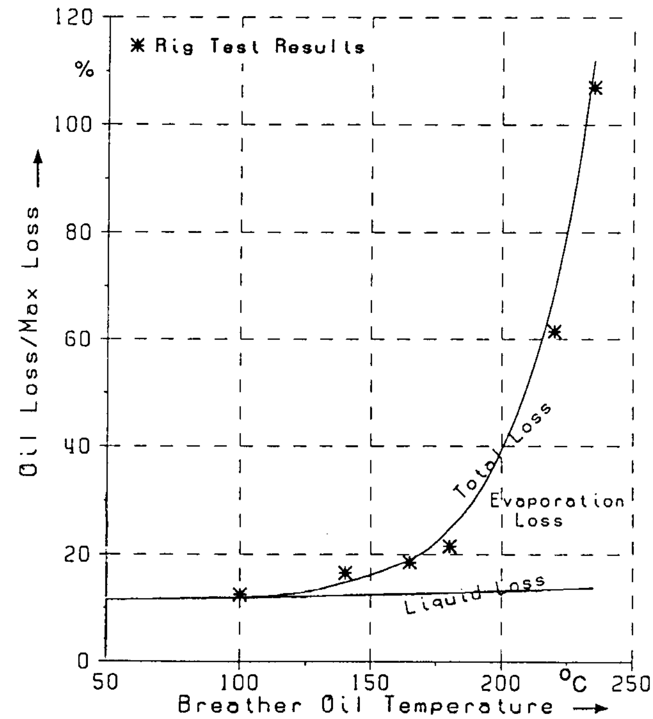

Fig.2 Breather Oil Loss v/s Temperature

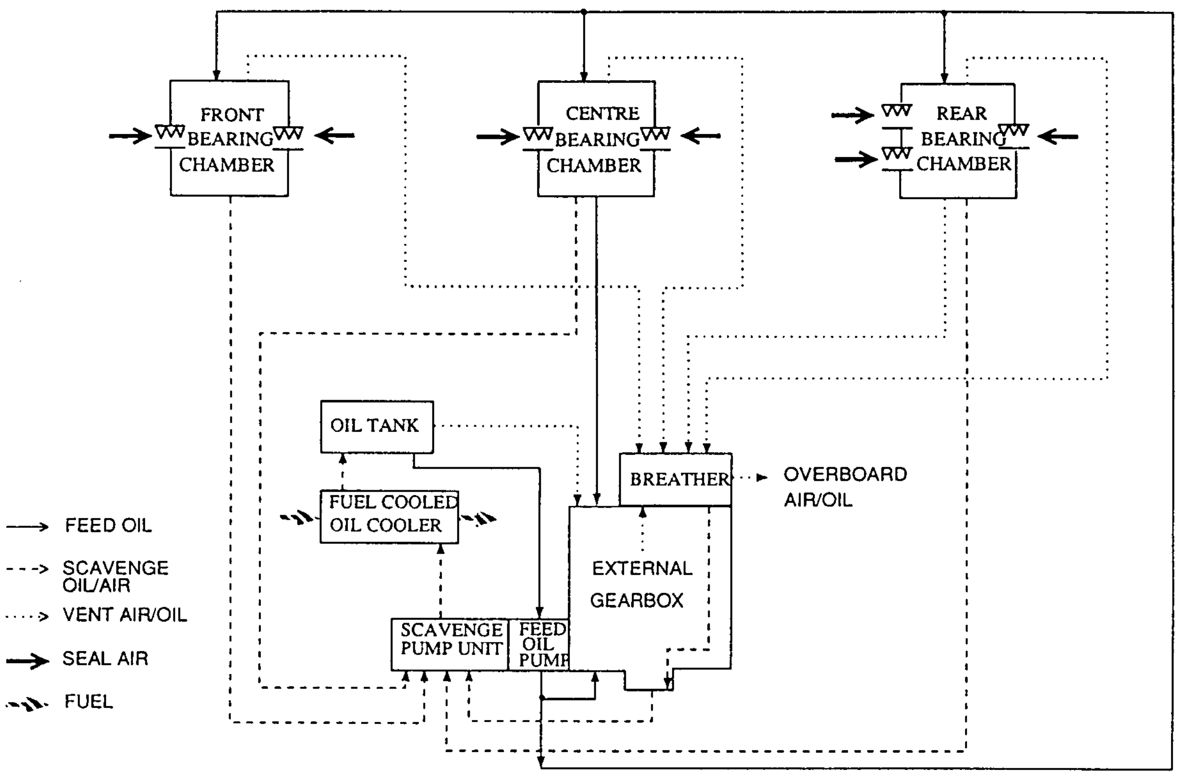

Fig. 3 Oil System Schematic

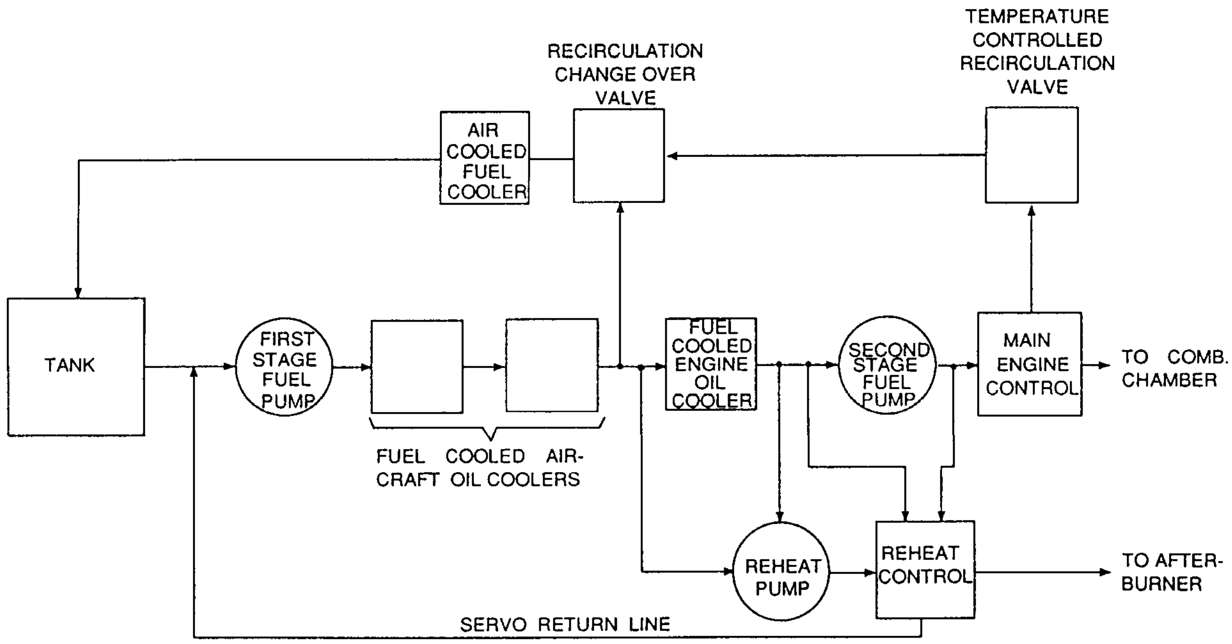

Fig. 4 Tornado/RB199 Fuel System Schematic

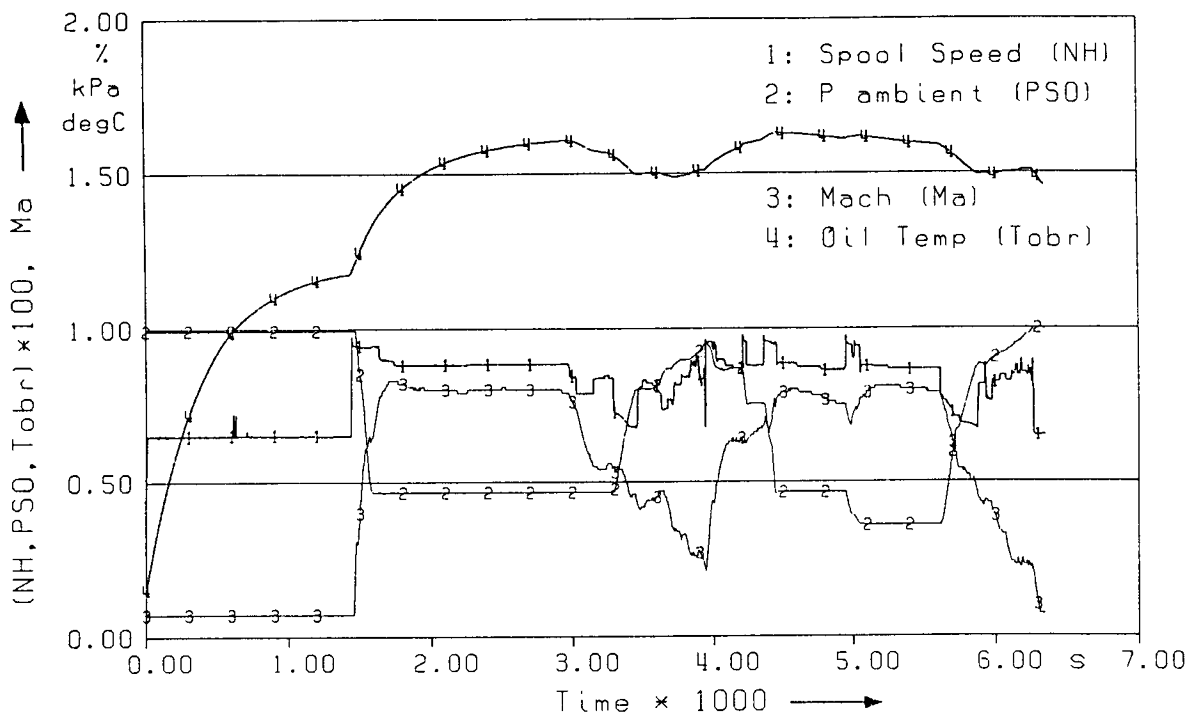

Fig.5 Calculated Breather Oil Temperature for Recorded Flight

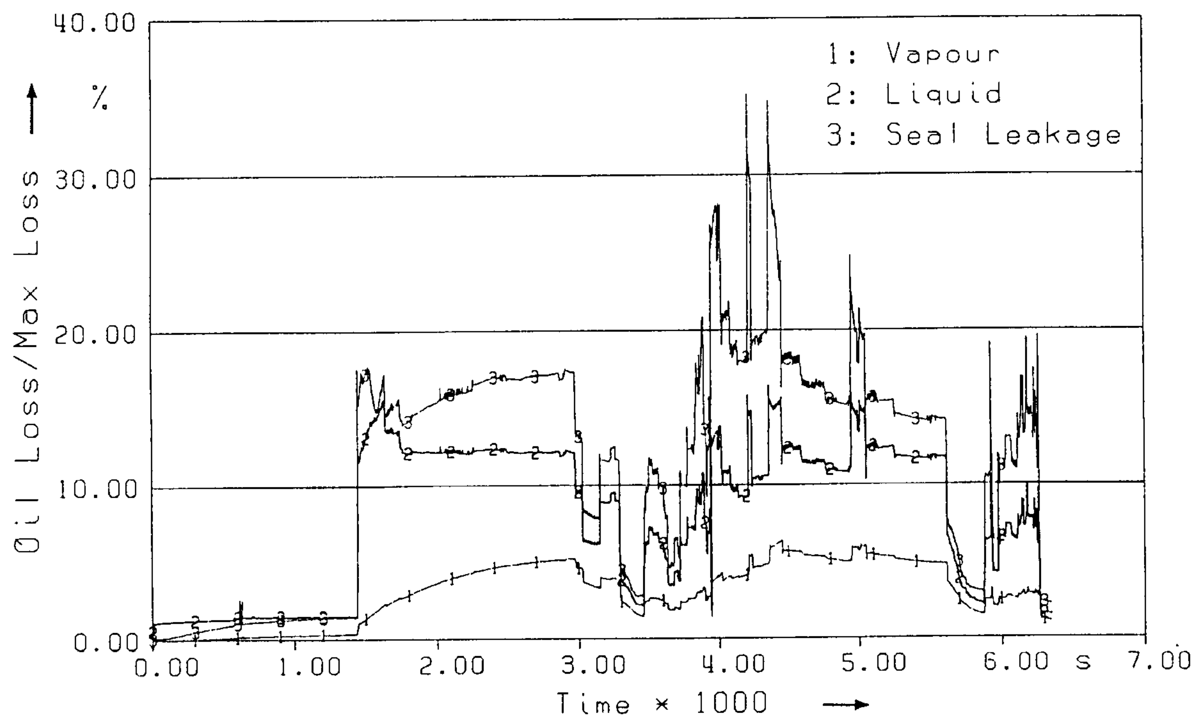

Fig.6 Calculated Oil Loss Through Breather and Seals

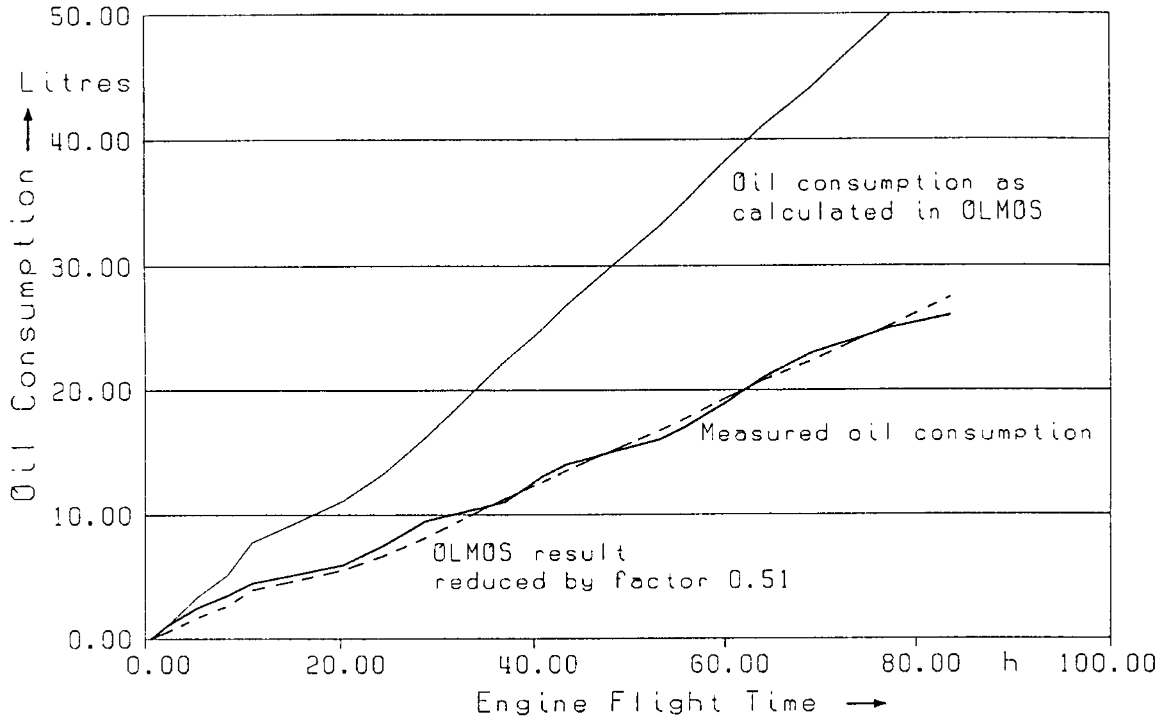

Fig.7 Comparison of Measured and Calculated Oil Consumption

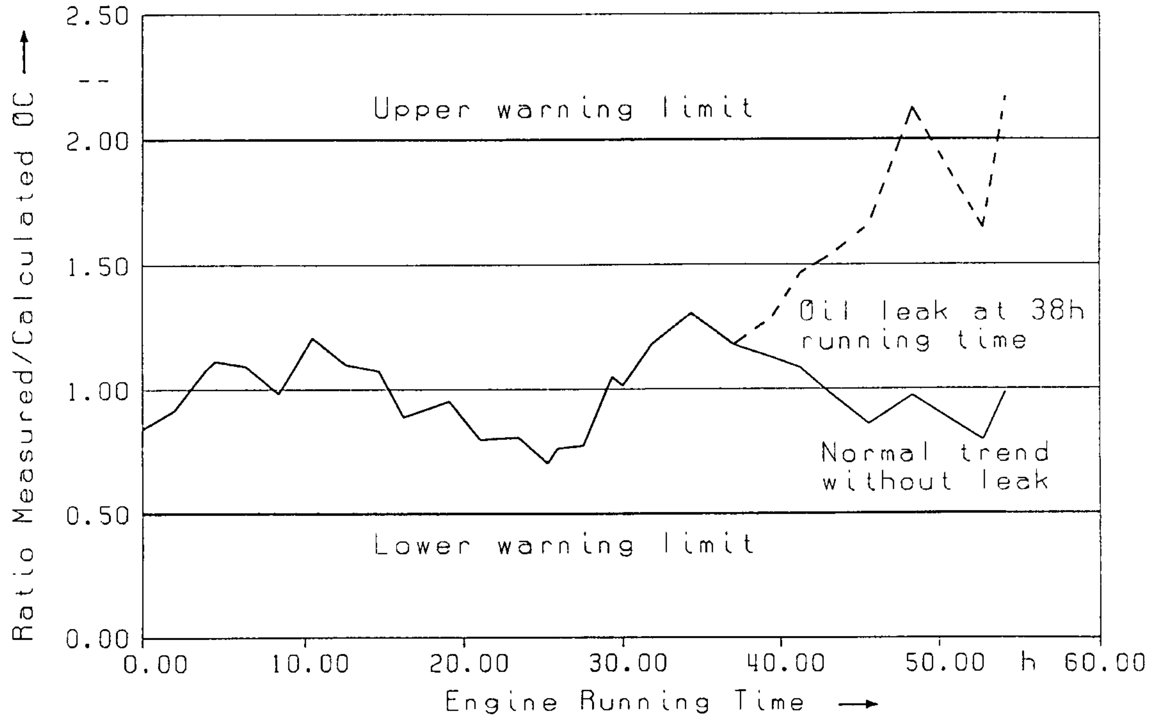

Fig.8 Trend of Ratio Measured/Calculated OC (10h-averaged)