MODEL-BASED DECISION SUPPORT TOOLS FOR T700 ENGINE HEALTH MONITORING.

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ABSTRACT

This paper describes the progress made by DSTO in developing a model-based approach to the diagnosis and prognosis of engine gas path health in the Australian Defence Force (ADF) helicopters powered by General Electric T700 engines. In particular, two new model-based tools are presented: one for estimating power assurance and one for detecting abnormal engine operation. These tools have been developed to take advantage of the engine parameters recorded by modern Health and Usage Monitoring System (HUMS). Such systems are under consideration for fitting to ADF helicopters as part of mid-life upgrade and acquisition projects. The first tool, the T700 model-based power assurance estimator is proposed for use with the current Health Indicator Test (HIT) check and it links the HIT check value to the power available for a given flight condition and scenario of component degradation. The second tool, a combined model–based detector and fuzzy-logic decision-maker is proposed initially for use in a HUMS ground station to reduce the amount of data manually processed or interrogated. The DSTO developed MATLAB-Simulink true twin T700 engine model with its demonstrated accurate tracking of transient flight data provides the means of detecting major shifts in in-flight engine condition over a given flight. A fuzzy logic formulation then provides the means to automate this detection process and provide an end of flight estimate for future prognostic trending.

INTRODUCTION

An international collaborative program has been set up, under the auspices of the Aerospace Systems Group of The Technical Cooperation Program (TTCP), to develop new methods for the diagnosis and prognosis of engine gas path health in military helicopters. Participating nations include the United States, Canada, New Zealand and Australia. In this program, DSTO has taken the lead role in developing model-based methods for helicopters powered by the General Electric T700 turboshaft engine [1].

The collaborative program seeks to provide both maintenance and mission planners with better decision-making tools for assessing firstly, the gas path condition of in-service turboshaft engines and secondly, the mission-worthiness of the engines. Maintenance planners require an enhanced capability to assess gas path condition to ensure that the on-condition maintenance policy of modern turboshaft engines is operationally effective. Mission planners also require new tools to relate the condition of in-service degraded engines to the power available at any part of the flight envelope. Such power assurance algorithms will enable decisions on system suitability for full missions and provide the ability to plan and schedule reduced capability missions.

Gas Path Analysis (GPA) serves a different role to the other main Health Monitoring Technologies of Vibration Analysis (VA) and Oil Condition Monitoring (OCM). VA and OCM attempt to diagnose events that lead to catastrophic failure of an engine component, and so they have a safety or airworthiness impact. In contrast, GPA attempts to diagnose events that lead to graceful failure in the function of the engine (degradation), and so it has a performance or mission-worthiness impact.

GPA seeks to diagnose the loss of engine condition due to causes such as: eroded, corroded and fouled blades and vanes; tip clearance changes, turbine bowed vanes and blade untwist; bleed and air-seal leaks, mis-scheduled variable geometry, control system failures and sensor failures. GPA seeks to infer the condition of the engine’s gas path from the changes in the engine’s thermodynamic parameters, ie the measured pressures, temperatures, speeds, torque, air and fuel flows, from their reference values. In the model-based approach, the engine model provides these reference values.
However, on current production engines, the isolation of gas path faults to a modular level has proven to be a difficult task given the limited set of engine gas path parameters that are available. Production engines are typically instrumented to measure torque, engine speed, power turbine speed and turbine gas temperature, and to a lesser extent to measure fuel flow and compressor pressure. Indeed, this situation, of a lack of gas path instrumentation, has not improved with the proposed new Health and Usage Monitoring Systems.

For the above reason, DSTO has focused initially on the development of improved tools for assessing overall engine condition and power assurance so that better decisions can be made on when to remove an engine. Two such tools, a model-based power assurance estimator and a combined model–based detector and fuzzy-logic decision-maker are presented below.

WHY A MODEL-BASED APPROACH?

DSTO has pursued a model-based approach to the development of improved tools for the diagnosis and prognosis of engine gas path health, as a result of two earlier analyses of existing and proposed health monitoring methods.

In the first study, the usefulness of the existing Health Indicator Test (HIT) was assessed. The HIT check is used by Black Hawk operators as a first flight of the day check on engine condition. The HIT check indicates whether an engine has suffered a significant performance shift; it is a simple measure of the difference of the Turbine Gas Temperature (TGT) from a reference value at a low power setting of 60% Torque (TQ). A fleet-wide analysis of Australian operations showed that useful trends in long-term condition could be extracted from the HIT check records, even given the ±12°C uncertainty in the individual HIT check values. The average fleet-wide trend showed a 2.5°C increase in TGT per 100 engine hours.

Whilst these long term trends provide useful indicators of engine condition, what is missing in the current HIT check procedure is a link between how hot the engine is running - the TGT margin - and what power is available across the flight envelope. Carrying out a power check at the maximum TGT limiter setting does provide a measure of the maximum power available but it is not suitable for a daily check. Firstly, not all missions require the assurance of maximum rated power. Secondly, the in-flight test manoeuvre is more time consuming than is desirable for a quick daily engine check. Thirdly, and most importantly, such excursions to maximum power are detrimental to engine life and so unnecessary operation at maximum conditions should be avoided. Consequently, the use of a model-based approach was seen as the way to relate the daily HIT check margins to the power available and to minimise the number of power checks required.

In the second study, the usefulness of a new Power Performance Index (PPI) developed by General Electric was assessed. DSTO participated in this assessment as part of a TTCP collaborative effort with the US Navy on its Helicopter Integrated Diagnostic System (HIDS) program [2]. Essentially, the PPI is based on the difference between the operating TGT and a simple TGT versus Torque (TQ) reference curve. Overall, the PPI provided an improved HIT check, ie indication of condition, but not the required measure of acceptable power. It extended the application of the HIT check from the specified 60% TQ value to a range of low to medium power levels but it was not applicable to the higher engine power settings. The resultant increased capture of PPI values, from the one value a flight for the HIT check to some two hundred PPI values over a flight, provided sufficient numbers of PPI estimates to establish an accurate end of flight indicator of condition. However, it suffers from the same weaknesses as the HIT check and for the same reasons a model-based approach to power assurance was deemed necessary.

T700 TURBOSHAFT ENGINE

The General Electric (GE) T700 turboshaft engine [3] powers three helicopters in the ADF fleet, the Sikorsky Black Hawk and Seahawk and the Kaman Super Seasprite. The engine variants are respectively, the GE-T700-701A, the GE-T700-401C and the GE-T700-401. As well as the above helicopters, the T700 engine powers a number of other helicopters operated by TTCP nations, such as the Cormorant, Apache, and Cobra.

Figure 1: Twin Engine Installation [3]
The T700 engine is designed as a modular engine with four main modules, they are: cold section, hot section, power turbine section, and accessory section. The basic T700 engine system is controlled through the interaction of an Electrical Control Unit (ECU) and a Hydromechanical Control Unit (HMU). The engine control system provides for the more common functions of fuel handling and computation, compressor bleed and variable geometry control, power modulation for rotor speed control, over-speed protection, and load sharing between engines for multiple-engine installations. Importantly, the propulsion systems of the ADF helicopters consist of two T700 engines operating in parallel with torque matching. This is illustrated in Figure 1.

MODEL-BASED POWER ASSURANCE ESTIMATOR

The T700 Model-Based Power Assurance Estimator was developed to provide a capability to assess the power available from a twin engine helicopter when the two engines are operating with significantly different levels of component degradation. Traditionally, simulations and mission planning studies have modelled the performance and behaviour of twin engine helicopters by simply doubling the power available from a single engine of specification performance.

The function of the model-based estimator is to link the operational indicator of overall engine condition with the power available at a specified flight condition and component degradation scenario. In the case of the current T700 engine health monitoring scheme, the manually recorded HIT Check, the estimator links the operational HIT check TGT values (how hot the engines are running) with the power available. In the case of a future HUMS, operating the proposed automated engine health detector, the estimator will link the end of flight estimate of engine condition with the power available.

Adaptive Degradation Model of the T700 engine

The key activity in the development of the power assurance estimator was the development and validation of an adaptive degradation model of the T700 engine. The adaptive model provides the required capability to model engine operation under varying scenarios of component degradation. It is based on a high fidelity, transient, aerothermodynamic model of the T700 engine that was developed by NASA Ames [4,5] and coded as a Fortran computer program. In the NASA model, the engine was modelled as four major thermodynamic components, a compressor, combustor, gas generator and free-power turbine. As well, the NASA model included a comprehensive set of models of the HMU and ECU.

The NASA model was modified by DSTO to adaptively implement the effect of changes to the major component characteristics. These components included: the intake, the scavenge and anti-ice and starting bleeds, the compressor, the compressor and customer bleeds, the combustor, the gas generator turbine, the power turbine and the exhaust nozzle. The component changes or deltas were introduced in two parts. The first part covers engine to engine variations. This handles the use of different T700 engine versions, such as -700, -701A, -701C, -401, and -401C, as well as the normal fleet-wide variations seen in healthy engines, the result of build variations, and so provides the initial individual engine baseline against which to trend performance changes. The second part covers the component degradation – the changes- from the initial baseline.

The T700 adaptive degradation model was validated against a database of manufacturer's specification data and US Navy test-cell data. The database included: GE specification model data for the T700-701A and T700-401C engines; and US Navy HIDS test-cell data for some five engines, of which three engines were rejected, from the fleet, for performance related problems. The adaptive model was shown to be able to provide a good fit across the power range for each engine. The model matches the GE specification data on major thermodynamic parameters to better than 1.5% overall. The model's fidelity was found to be more than adequate for the purpose of power assurance, although some further refinements will be necessary for modular diagnostics.

Model-Based Sensitivity Analysis

The relationship between the change in the HIT check TGT temperatures and the power available, under different scenarios of component degradation, was established by a model-based sensitivity analysis. This analysis examined the effect of degradation in the three major gas path components, the compressor, the gas generator turbine and the power turbine; and it involved scenarios of both single and multiple component degradation. The results of this analysis have been incorporated into the Power Assurance Estimator program.

Using the T700 adaptive degradation model, the individual characteristic component maps of the compressor, gas generator turbine, and power turbine were changed to model the effect of degradation. The two dimensional domain of all possible component degradations was generated by varying the characteristic parameters of efficiency and mass flow by up to five percent from their reference values. Five per cent was considered to be a realistic upper limit beyond which the component
degradation was expected to be very obvious and out of the region of interest.

For each component, the following process was followed. Firstly, the T700 adaptive degradation model was run to calculate the changes in TGT at the HIT Check power setting of 60% Torque. Secondly, the contours of TGT changes, in intervals of 10 °C, were calculated across the component degradation domain. Thirdly, for each HIT check TGT contour, the efficiency and mass flow parameter pairs were extracted. Fourthly, the model was re-run at the maximum rated power setting, maximum TGT, using the appropriate efficiency and mass flow degradation pairs calculated above. This provided the estimate of the power available for an engine operating at the given HIT check TGT value under the proposed degradation scenario. Fifthly, this was also done for the two other engine parameters available on the Black Hawk, the gas generator speed (NG) and the fuel flow.

The results for the case of compressor degradation are presented here. Figure 2 shows the contour plot of HIT check TGT increases for the given degradation domain. It also includes a specific fault signature for changes to compressor rotor tip clearances. This signature was extracted from an early experimental study by DSTO on a similar turboshaft engine [6,7]. Figure 2 also shows the resultant drop in power for HIT check margins of 20, 40 and 60 (°C). Whilst the band of possible power drops for the given domain of compressor degradations is reasonably wide, some 3 to 4%, it does provide a good guide to the HIT check value at which the engine will fail the power check - at some 8% below specification power. The narrower power band for the compressor tip clearance fault clearly demonstrates the benefit of knowing the fault signature more accurately, in terms of the component efficiency and mass flow pair. Here, there is good discrimination (no overlap) between the power loss at each HIT check level.

Some typical power loss results for a range of single and multiple component degradation scenarios are shown in Figure 3. These are for a HIT check TGT rise of 40 °C. The multiple component scenarios involve any two of the three components, combined together in the proportions of 25/75% and vice versa, and 50/50%. The single component only is 100%. The results show a wide range of possible power check values for a given HIT check of 40 °C. Importantly, for correct engine matching, the results were very sensitive to the introduction of power turbine degradation. In combination with either compressor or gas generator turbine degradation, the power turbine degradation produces a significant increase in the possible power loss. In such circumstances, the engine may reach
the minimum acceptable power range at a relatively low HIT check TGT value of 40 °C.

**Model-Based Power Assurance Estimator Program**

A demonstrator version of the T700 model-based power assurance estimator has been developed for use with ADF Black Hawk helicopters [8]. Initially, this demonstrator version is to be trialed by ADF logistic personnel to assess its usability and, in particular, its usefulness for scheduling overhauls of an aging engine fleet.

For ease of operation, a user-friendly interface has been developed using the Microsoft Excel programming environment. The underlying model-based estimator programs, which are coded in Fortran, have been included in the Excel program via a Dynamic Linked Library (DLL) file. The Excel user interface performs a number of input, intermediate and output functions. On the input side, it allows the operator: to choose how hot the engines are running as indicated by the Health Indicator Test check; to choose an appropriate component degradation scenario for the engine; and to select and input the required operational conditions of altitude, speed, load and hence the corresponding torque required from the flight manual, or to select a pre-set sample of flight conditions. On the output side, it provides the power available, and the margin of power remaining at the various engine power ratings, for the specified flight condition and scenario of engine degradation. The main result screen - the T700 Power Margins screen - is shown in Figure 4.

To provide the required results, the Excel program essentially runs the single engine open loop T700 adaptive degradation model three times. The first time to predict the reference or specification engine performance to establish the expected flight manual or normal performance for the given ambient conditions. The second time to predict the left engine performance with its given level of component degradation or condition. The third time to predict the right engine performance with its given level of component degradation or condition. The program provides the torque available at the maximum continuous, maximum and contingency power ratings, as well as indicating how close the engines are operating to the various turbine gas temperature limits, gas generator speed limits, and fuel flow limits.

In the current demonstrator version, the choice of degradation scenario has been limited to either degradation of the cold end (compressor) or the hot end (gas generator)....
turbine). As illustrated in Figure 5, the full two-dimensional domain of possible efficiency and mass flow pairs have been separated into four separate regions, each represented by a given average signature. The program uses these signatures to extract an estimate of the component degradation given the level of the TGT margin input from the operational HIT check. The resultant pair of efficiency and mass flow changes is then used, in the model, to generate the power margin. Currently, a fleet-wide analysis of the repair and overhaul history of the T700 engines is being undertaken to generate better information on the plausibility and probability of the possible degradation scenarios.

Recently, the Black Hawk demonstrator version [8] was upgraded to include a prognostic capability. This capability provides estimates of the number of flights to minimum acceptable engine performance and the likely condition/performance of an engine after a specified time, eg field deployment. Currently, the fleet-wide rate of engine deterioration has been estimated from a historical analysis of the HIT check trends covering half the ADF Black Hawk fleet. This analysis is being extended to cover the whole fleet.

The current status of the Black Hawk model-based power assurance estimator is that it is ready for evaluation by logistic personnel, as to its usefulness. Furthermore, this evaluation should help to identify the changes required to tailor this diagnostic tool to the way the Black Hawk is operated. In the near future, it is proposed to develop similar versions for the Seahawk and Super Seasprite helicopters.

**AUTOMATED GAS PATH CONDITION DETECTOR**

An automated model-based gas path condition detector has been developed to take advantage of those modern Health and Usage Monitoring Systems (HUMS) that record engine parameters in-flight, for the entire flight.

Its prime functions are as follows. Firstly, to detect significant shifts in engine condition, and or abnormal operation, over a single flight. Secondly, to provide an end of flight estimate of engine condition for trending of long-term degradation, and prognostics. And, thirdly, by automating the above processes, to reduce the need for maintenance personnel to manually screen each set of flight data for abnormal events.

The development of the detector involved a two-step hybrid approach. It required the formulation of a new twin engine model capable of tracking transient engine operation, and the formulation of a fuzzy-logic scheme capable of automating the decision making process. These two developments are described below.

**Matlab-Simulink True Twin T700 Engine Model**

The Fortran coded NASA model, used in the power assurance work, was not suitable for the detection task as it did not run as a true twin engine closed loop model – it only worked as a single engine with overall engine power doubled. Therefore, it was proposed to develop a T700 engine model using the MATLAB® simulation environment and its Simulink® Toolbox – here after referred to as the Simulink model. The Simulink model was seen as a solution to this problem as Simulink is capable of handling the parallel operation of two engines in a closed loop environment.

The Simulink modelling environment has proved to be very useful, in that, it offered many advantages over the normal Fortran language, in terms of model development, validation and operation, and it also opened up many new capabilities. The Simulink model was relatively quick and easy to develop and it was easy to manipulate once built. It was also easy to see how it worked as a Simulink model is, itself, a schematic block diagram. Furthermore, it facilitates interactive studies, as the inputs and model parameters are accessible during the simulation.
The ability of the Simulink model to truly implement the twin engine torque share, as carried out by the Electrical Control Unit (ECU), by itself, opened up a number of useful capabilities. These capabilities included: the ability to look at condition assessment and fault diagnosis from transient flight data; the ability to look at engine control related problems; the ability to look at retro-fitting Full Authority Digital Electronic Control Systems (FADECS); and the ability to look at care-free handling issues. As well, the use of the MATLAB environment facilitates the use of other advanced analytical tools, as they can be readily used and interfaced with the Simulink model. These include such MATLAB analysis toolboxes or extensions as, signal processing, parameter identification, robust control and fuzzy logic toolboxes, and the MATLAB Real-Time Workshop™, etc.

The T700 Simulink model, developed by DSTO, is described in Reference [9]. It describes the development, structure and usage of the twin T700 engine Simulink model. The underlying thermodynamic equations are taken from the T700 engine model developed by Ballin [4].

The T700 Simulink program enables the user to select and model one of three engine system configurations. These system configurations are: a single engine without control system (open loop); a single engine coupled with its control system; and a twin engine system, with the two engines and control systems running in parallel and coupled together by torque sharing logic. Each of these three engine systems has been built with the capability to simulate the effect of changes to the condition or performance of the aero-thermodynamic characteristics of the major engine components, as described above in the T700 adaptive degradation model. The twin and single engine block diagrams are shown in Figures 6 and 7, respectively, while the block diagram for the ECU is shown in Figure 8.

The main weakness of the Simulink model is that it is not a real-time model, however, the simulation times are reasonable for interactive and development studies. This weakness has been overcome by the use of the MATLAB Real-Time Workshop toolbox. This toolbox automatically converts Simulink code into real-time source code, and generates the appropriate executable real-time code for the specified target machine or board. This is a quick and easy process providing standard C code. Overall, these MATLAB tools provide an excellent capability for rapidly developing diagnostic prototypes for use in ground-based HUMS computer stations or in on-board HUMS computers. All the T700 Simulink models have been successfully converted to real-time models using the Real-Time Workshop toolbox.
Ability of the T700 Simulink Model to Track Flight Data

The ability of the twin engine Matlab-Simulink model to track transient engine performance was assessed by comparing the model predictions with the data recorded by the US Navy’s SH-60 HIDS flight trials. This assessment sought to establish the model’s usefulness for detecting major shifts in in-flight engine condition.

Whilst the flight profiles generated by the SH-60 HIDS flight trials do not cover the full spectrum of military operations they do cover a sufficient range of flight operations such that a realistic assessment can be made of the model’s ability to track operational data. For the assessment, the torque and collective profiles were classified as one of two types of flights, or sections of flights. The first type covered flights with few major transients and many near steady-state portions, and the second type covered flights with frequent minor transients and few steady-state portions.

The first type of flight should be typical of missions with long cruise legs and high loiter times. The implication of this behaviour is that a steady-state based estimate of condition may be sufficient. The second type of flight has rapid variations in torque where the torque variations are not measurement noise but rather the actual transient response of the engine to pilot inputs through the collective – the load demand spindle. Such behaviour should be more typical of missions with continuous flight or combat manoeuvres. The implication of this behaviour is that a transient model would be required to provide sufficient in-flight estimates of engine condition, i.e. high in number and low in uncertainty.

The T700 Simulink model was tested against data from some thirty HIDS flights, each of around fifty minutes in duration. Over the period of these flight trials, three T700-401C engines were installed in the test aircraft. The right engine was removed and replaced mid way through the flight tests. As all three engines produced near specification power levels, it was expected that a T700-401C model of near specification performance should fit the flight data.

However, for the same load conditions, there were small differences between the left and right engine measurements of interest, i.e in the speeds, pressures, temperatures and fuel flows. These differences were attributed to engine to engine build variations and not to the presence of significant levels of component degradation. The NG and TGT differences were 0.7% and 4°C for the first set of flights, and -0.1% and -13°C for the second set of flights.

![Simulation of Flight with Frequent Minor Transients](image)

*Figure 9: Tracking Capabilities of Simulink Model*
Consequently, the above parameter differences between the left engine and right engine provided an estimate of that part of the error between the model simulations and the flight data – or bias error - which could be attributed to actual engine to engine variation rather than model error. The model simulations were carried out using the following input parameters, the ambient temperature, pressure altitude, torque, and load demand collective. These parameters were extracted from the HIDS flight data that was acquired at one hertz.

Overall the model’s ability to track the two type of flights was excellent. This is illustrated in Figure 9, it is for the second type of flights, those with frequent minor transients. The plots show that there is a small bias between the model predictions and the measured values of NG and TGT. The magnitude of this bias, or model error, is directly related to the torque level. The bias is -0.5% NG and 10°C TGT at the lowest power setting and it increases by another -1% NG and 10°C TGT at the highest power setting.

The accurate tracking provided a consistent and numerous (at one hertz) set of parameter differences for a single flight. These NG and TGT differences were averaged to form an end of flight indicator of condition for each of the thirty HIDS flights. With a correction for the TQ bias, the 2σ scatter bands (or uncertainty) about the mean of the end of flight estimates of NG and TGT were ±0.4% and ±10°C, respectively. This parameter uncertainty is within the 3% change in NG and the 50°C change in TGT margins that the model studies have shown to be associated with a degraded engine reaching minimum acceptable performance. Consequently, the T700 Simulink model can be used to detect significant changes in engine condition over a single flight. As well, it can be used to generate an end of flight indicator of condition that is suitable for trending.

**Fuzzy-Logic Scheme to Automate Detection Process**

The automated detection scheme was developed, initially, for use in a HUMS ground station where its role is to determine whether significant changes in engine condition have occurred within a flight, and if not, provide an end of flight estimate of condition for future prognostic trending. Given the high reliability of modern T700 engines, under normal operational conditions, the occurrence of abnormal engine behaviour is likely to be a very infrequent event. However, when it does occur it must be detected, as soon as possible, and reliably so.

In this context, the benefits of the automated detector are: its capability to detect such abnormal operation within a single flight, and its ability to significantly reduce the amount of flight data that needs to be manually screened and processed by maintenance analysts, at the ground station. Flights that are judged normal will be sent straight to archive, without further reference to an analyst, with only the single end of flight estimate being saved, at the ground station, for trending the long-term shift in engine condition. Flights that are judged abnormal will provide an alert to the ground station analyst, and only these flights will need to be reviewed by the analyst.

Fuzzy logic was seen as a robust and practical way of automating the detection process. Indeed, the strength of fuzzy logic is its ability to deal with decision-making in an environment of uncertainty and imprecision, which is the case here.

In contrast to the more traditional numerical methods, fuzzy logic mimics human reasoning through the use of linguistic variables whose values are words rather than numbers. Such linguistic variables are represented by fuzzy sets and are defined by a membership function. The membership function relates the numerical value of some parameter, generally measurable, over a given domain to its degree of membership of a linguistic variable. Consequently, this membership function provides the means to represent imprecision or fuzziness. The role of approximate reasoning is carried out by a series of fuzzy if-then rules involving the various linguistic variables. Importantly, all these rules or propositions are evaluated in parallel, and not in series as in conventional expert systems. The final stage of the fuzzy reasoning process is called defuzzification. Here, the solution linguistic variable, or output fuzzy variable, is converted to its expected numerical value. The fact that both the inputs and outputs of a fuzzy logic scheme are crisp - measurable - numbers means that it can readily be used in many practical applications, eg control of complex machines.
Fuzzy-logic was used to carry out three tasks, they were: to correct the biases in the Simulink model output; to determine the instantaneous level of engine condition at each flight data point; and to combine the instantaneous indicators into an overall end of flight indicator of condition. These three tasks were implemented using the Matlab fuzzy logic toolbox and the Simulink coding environment. These three tasks are described, in more detail, below.

The role of the T700 Simulink model in the detection scheme is to provide the reference point, for an engine in good condition and behaving normally, against which current engine behaviour can be compared. Whilst the T700 Simulink model has demonstrated a capability to accurately track real engine data, small model biases did exist and these needed to be corrected for to provide a more accurate end of flight indicator. The process of manually correcting the biases at the end of each flight, as done in the evaluation of the T700 Simulink model, was a tedious and time consuming process, and so an automated approach to the task was sought.

The first fuzzy system determines the bias correction for each of the two gas path parameters of interest, TGT and NG, and corrects these parameters before feeding them forward to the next fuzzy system. It also determines the nature of the engine behaviour and feeds this value forward for use in the next fuzzy system. The extra output linguistic variable – engine behaviour – provides a means of handling the higher uncertainty associated with transient operation or more extreme flight manoeuvres. For example, a section of flight can be considered as being somewhat transient, and does not need to be classified as either fully transient or fully steady state. Therefore, this variable allows the resultant error between the flight data and the model prediction to be greater during operations other than steady state. The relaxation of the permissible error reduces the likelihood of the detector generating false alarms during transient operations.

The inputs and outputs of the first fuzzy inference system are illustrated in Figure 11. These are all evaluated at the flight data acquisition rate of one hertz. The inputs are the instantaneous torque, delta torque (the model torque output – instantaneous torque), load collective, torque split, and outside air temperature. The observed relationship between the model biases and, the level of engine torque, and Outside Air Temperature, were used to generate the membership functions for the input and output linguistic variables, and the appropriate inference rules. This first fuzzy system is made up of some 13 if–then logic rules.

The second fuzzy system is used to determine the significance of the error between the engine and the
reference Simulink model, at each instance of the flight. Hence, it seeks to provide an instantaneous indication of engine condition throughout the flight.

The inputs and outputs of this second fuzzy inference system are illustrated in Figure 12. These are again evaluated at the flight data acquisition rate of one hertz. The inputs are the engine behaviour variable, and the corrected model error of TGT and NG. The outputs are the instantaneous levels of degradation of TGT and NG. Essentially, the membership functions and inference rules were generated heuristically. The engine behaviour variable allowed greater error levels during transient operation and lower error levels in steady-state operation. The interface used to generate the membership functions, fuzzy sets, is illustrated in Figure 13. It shows the output linguistic variable for the degradation level of TGT. The five fuzzy sets are all_OK, low_caution, caution, high_caution, and warning. Some 42 if-then rules were used to determine the instantaneous level of degradation.

The third fuzzy inference system involves a two step process to determine the end of flight estimate of condition. In the first step, the five output degradation variables are input into a fuzzy system that examines the instantaneous degradation level over an eight point interval to eliminate rogue error spikes, and reduce the output variable to only three possible outcomes. These are: all_OK, caution, and warning. The typical output of this system is shown in Figure 14. In the second step, the overall end of flight indicator is generated. For this purpose, as illustrated in Figure 14, the flight is separated into 5-minute sections, and with the use of fuzzy logic, the classification of each section is determined. A final classification of the flight is determined by inputting the classifications of the current and previous sections, together with their location in the flight into a final fuzzy system. This system adds extra weight to degradation occurring at the end of the flight, and less to degradation occurring at the start of a flight.
A Matlab interface has been developed to display the overall results of the detection process and to allow an analyst to further interrogate the results, if desired, right back to the HUMS flight parameters. The high level interface and a secondary interface are shown in Figures 15 and 16, respectively. This interface will facilitate the assessment and verification of the automated detector’s performance.

The detector has been tested against flight data from some thirty SH-60 HIDS flights and it appears to be quite robust. Importantly, for these good engines it did not generate false alarms when dealing with the wide range of flight conditions involved. The detector’s performance in dealing with abnormal operation was assessed by simulating engine degradation, through variations in NG and TGT over the flight. Figure 14 is an example of a flight where a 30°C bias was added to the TGT profile. In this case, the detector produced the appropriate end of flight caution. Indeed, the performance of this initial formulation has been better than expected and it is handling this complex task with relative ease. What now needs to be done is to extend the evaluation to a much larger sample of HUMS flight test data. This will be carried out under the auspices of the TTCP collaborative program.

CONCLUSION

Good progress has been made towards the development of model-based decision support tools for T700 engine health monitoring. Two prototype tools have been presented here, the Model–Based Power Assurance Estimator and the Automated Gas Path Condition Detector. These tools are proposed for use in military helicopters that will be retrofitted with modern Health and Usage Monitoring Systems (HUMS), in particular, with HUMS that record engine parameters over the entire flight.

The capabilities of both prototypes have been successfully demonstrated against a limited set of operational and trial data. The next step is to undertake a more comprehensive evaluation of these tools using data from Australian Defence Force Black Hawk operations, and from the US Navy Integrated Mechanical Diagnostics Program’s flight trials.

REFERENCES


