A Hierarchical Framework for Fault Propagation Analysis in Complex Systems

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Abstract— In complex systems, there are few critical failure modes. Prognostic models are focused at predicting the evolution of those critical faults, assuming that other subsystems in the same system are performing according to their design specifications. In practice, however, all the subsystems are undergoing deterioration that might accelerate the time evolution of the critical fault mode. This paper aims at analyzing this aspect, i.e. interaction between different fault modes in various subsystems, of the failure prognostic problem. The application domain focuses on an aero propulsion system of the turbofan type. Creep in the high-pressure turbine blade is one of the most critical failure modes of aircraft engines. The effects of health deterioration of low-pressure compressor and high-pressure compressor on creep damage of high-pressure turbine blades are investigated and modeled.

I. INTRODUCTION

Complex engineering systems consist of large number of components and each component might fail in multiple ways. Each failure occurs under the effect of one or many fault modes. Condition-based maintenance/prognostic health management (PHM/CBM) technologies aim at improving the availability, reliability, maintainability, and safety of such systems through development of fault diagnostics and failure prognostic algorithms. To fully enable the predictive element of these technologies, the key is the ability to understand the fault-to-failure progression characteristics, not only of the faulty component but of the complete system.

Complex systems consist of large number of components and each component might fail in a multiple ways. Each failure occurs under the effect of one or many fault modes. When a fault condition arises in one of the components, not only that component’s behavior but the interaction of that component with the other components/subsystems also changes. However, the effect of that change on other components/subsystems may be different in severity. Some of the components/subsystems might be adversely affected while others might not be affected at all. This might give rise to more faults in the same or the other components/subsystems. The subsequent faults may be different from the original fault in terms of not only severity and criticality but also the propagation dynamics. It is possible that the original fault might not be as critical in itself but the faults occurring due to this fault may be detrimental. For example, compressor fouling rate leads to a reduction in gas-turbine blade life [1]. Compressor fouling fault is not critical to the engine in itself but degraded gas-turbine blades may lead to system failure. In many cases, fault in a component results in an overall reduction in system’s performance. Closed loop control attempts to compensate this performance reduction by increasing stresses on some other component in that system, thus causing other faults to evolve. To distinguish the fault evolution within a subsystem from spreading of effects of the fault to other subsystems, the former is hereafter referred to as fault progression and the latter as fault propagation. In Figure 1, a system consisting of two subsystems A and B is shown. An arbitrary fault, say fault I develops in the subsystem A. Fault progression modeling aims at estimating the evolution of fault I under the given operating conditions/use strategy, while fault propagation model estimates effect of fault I on another fault II in subsystem B. An energy flow approach for fault propagation analysis was proposed by the authors in [2]. In this approach, the rate of exergy destruction was used as a measure of thermal stress on aircraft engine subsystems.

In the present paper, fault progression/propagation has been analyzed via physics-of-failure (PoF) mechanism approach. An aeropropulsion system of turbofan type has been used as the application domain. In most of the cases, engine failure occurs as a result of HPT blade cracks. In HPT turbine blade, there exists two dominant failure mechanisms, i.e., creep and low-cycle fatigue. In this paper, it is assumed that creep is the only active mechanism. A simulation package of a commercial aircraft engine (C-MAPSS) is used to simulate faults in various subsystems of the engine. Based on the finite-element (FE) models of the blades (made of GTD-111 material) available in the open literature, the effects of faults in various subsystems on the creep life of the HPT blades are calculated. Though the results being presented are specific to the turbofan engine, the approach can be used for a variety of systems.

II. BACKGROUND

The results being presented in this paper are obtained using an architecture proposed by the authors in [3]. The architecture is primarily based on physics-of-failure (PoF) approach. However, unlike classical PoF methods, which are used at component-level, the proposed architecture presents a system-level approach for CBM/PHM technologies. A
hierarchical arrangement of the following types of parameters constitutes the structure of this approach.

1. System-level operating conditions.
2. Subsystem-level operating conditions.
3. Load conditions.
4. Subsystem properties.
5. Stresses.

These parameters are used in conjunction with 3 models to translate a given mission/cycle profile into the relevant stresses. The models used in the architecture proposed in [3], are:

1. A turbofan engine simulation model (C-MAPSS), a tool for simulating a realistic large commercial turbofan engine [4].
2. A subsystem properties model used to translate load conditions into relevant stresses.
3. A failure mechanism model for creep.

The subsystem properties model and failure mechanism models are then combined using design of experiments (DoE) methods, and a response surface metamodel is developed. The details of these models can be found in [5] and [3]. The overall utility of these models (C-MAPSS and response surface metamodel) is to calculate the consumed creep life for a given set of system-level operating conditions.

A typical flight cycle of a commercial aircraft consists of the following sequence of operating modes.

1. Takeoff
2. Climb
3. Cruise
4. Descent
5. Landing

Fig. (1) shows the amount of life consumed for a typical flight cycle of a commercial aircraft, while Fig. (2) shows the contribution of each phase in the consumed life (as a percentage of life consumed in the cycle). These plots are obtained under the following assumptions:

a) A certain set of operating conditions for each of these phases of operation (given in the Table 1).

b) All the subsystems in the engine are healthy.

It can be observed from this plot that more than 70% creep damage is caused during the climb phase. Obviously, there can be several variations of the system-level operating conditions for each of the operation phases. However, this paper does not deal with this aspect of the problem. It specifically investigates the effect of faults/deterioration of one subsystem on the other subsystems in the same system.

C-MAPSS has a set of 13 health-parameters inputs, which can be used to simulate the effects of faults and deterioration in any of the engine’s five rotating subsystems, i.e., fan, low-pressure compressor (LPC), high-pressure compressor (HPC), high-pressure turbine (HPT), and low-pressure turbine (LPT). As previously mentioned, HPT creep strain is a life-limiting failure mode in a gas turbine engine. However, creep is a slow process. On the other hand, compressor fouling, though not a critical fault mode in itself, occurs much frequently. Compressor fouling might result in accelerating the HPT creep strain. In other words, an interaction between fault modes (compressor fouling and HPT creep strain) may exist. This paper presents a general methodology using which such type of interactions between fault modes can be investigated. The results will subsequently be used in enhancing the accuracy and performance of the prognostic algorithms employed by CBM/PHM technologies.
TABLE I. OPERATING CONDITIONS FOR EACH OPERATION PHASE

<table>
<thead>
<tr>
<th>Operation Phase</th>
<th>System-level operating conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Takeoff</td>
<td>Takeoff speed</td>
</tr>
<tr>
<td></td>
<td>0.27 Mach</td>
</tr>
<tr>
<td>Climb</td>
<td>Aircraft speed</td>
</tr>
<tr>
<td></td>
<td>0.66 Mach</td>
</tr>
<tr>
<td>Cruise</td>
<td>Aircraft speed</td>
</tr>
<tr>
<td></td>
<td>0.72 Mach</td>
</tr>
<tr>
<td>Descent</td>
<td>Aircraft speed</td>
</tr>
<tr>
<td></td>
<td>0.60 - 0.30</td>
</tr>
<tr>
<td>Landing</td>
<td>Altitude (ft)</td>
</tr>
<tr>
<td></td>
<td>1000-0 ft</td>
</tr>
</tbody>
</table>

III. IMPLEMENTATION

C-MAPSS can be used to simulate effects of faults and deteriorations in any of the engine’s five rotating subsystems, i.e., fan, low-pressure compressor (LPC), high-pressure compressor (HPC), high-pressure turbine (HPT), and low-pressure turbine (LPT). In this paper, we seek to explore the following models (Fig. 3):

c) Fault progression model (HPT): Damage evolution in the HPT blades, assuming that no deterioration exists in the other subsystems.

a) Fault propagation model (LPC ---> HPT): The effects of LPC fault/deterioration on HPT blades.

b) Fault propagation model (HPC ---> HPT): The effects of HPC fault/deterioration on HPT blades.

Obviously, the damage accumulation depends not only on the health state of the subsystems but also the system’s operating conditions (e.g. ambient, temperature, aircraft speed), which vary according to the aircraft’s operation phase. Even within the same operation phase, the operating conditions will be neither constant nor identical. However, the scope of this paper is limited to investigating the fact that how a critical fault mode in a subsystem is affected by the health deterioration of other less critical fault modes, not necessarily in the same subsystem. To investigate this aspect of the problem, we benefited from our earlier finding that climb is the most crucial operation phase of the entire flight cycle. All the results being presented in this section are obtained for the climb phase (specified by the system-level operating conditions given in Table 1).

Health deterioration of the engine’s subsystems are simulated by reducing their respective flow capacities and efficiencies. On the basis of performance simulations by [6] and the performance deterioration models produced by [7] and [8], it is assumed that the low-pressure compressor’s fouling causes a 0.5% reduction in the flow capacities of compressors for every 1% reduction in their efficiencies. Similarly, [9] suggests that HPC deterioration causes its efficiency and flow to be changed with 1:1 ratio, while in the case of HPT, the efficiency and flow are changed with 1:0.1 ratio. A single term, ‘fault-index (FI)’ was defined to describe the combined effect of reductions in efficiency as well as flow capacity of these subsystem.

A. Design of Experiments (DoE) approach

A statistical design of experiment (DoE) approach was used to investigate the effects of health deterioration in LPC and HPC on the HPT creep damage. Response Surface Method/Design of Experiments (RSM/DOE) is widely used in system-level design to construct metamodels (response surface equations) that approximate relationship between responses and variables.

The design of experiments is an efficient sampling method. For each sampling point, experiments are conducted to compute the corresponding response value. Next, a low order polynomial response surface equation (RSE) is used to fit these values. As in many other engineering applications, the real relationship between the response variable and the control variables is difficult to ascertain. However, the true function can be approximated by a metamodel. Response surface method is one of the widely used metamodel-building techniques. It is based on a statistical approach to building and rapid assessing empirical models. By careful design and analysis of empirical data, or the results from simulations, the methodology seeks to relate and identify the relative contributions of various input variables to the system response.

In general, the true relationship between the response and related variables can be written as:

\[ R = \text{function}(x_1, x_2, \ldots) \]

Where R is the response (creep damage in this case), and \( x_1, x_2, \ldots \) are the control variables (FI of LPC, HPC, and HPT).
Response surface method uses a polynomial to approximate this function. A first-order RSE is shown as:

\[ R = b_0 + \sum_{i=1}^{k} b_i x_i + \sum_{i=1}^{k} \sum_{j=i+1}^{k} b_{ij} x_i x_j \]

To obtain the coefficients, response values for some combinations of variable values will be needed. One way to select the necessary combinations is through design of experiments (DoE), which is the application of geometric principles to statistical sampling to obtain desired results such as minimizing the number of experiments necessary to obtain the answer to a problem or minimizing the variance of estimated coefficients obtained through regression. Simply speaking, DoE is an efficient sampling method. An experiment can be a lab testing or Computer Simulation, from which a response value is obtained based on the combination of variable values. Various types of DoE are available to provide different sampling approaches. Selection of a certain type of DoE is based on balance between the cost/time for an experiment and number of experiments for a type of design of experiments.

B. Limitations of RSM/DoE

RSM/DoE provide an efficient and useful way for response function approximation. But, using a low-order polynomial based on a set of experiments to approximate an unknown function has its limitations. If the true function is monotonic, the RSE can reach a relatively good fitness to this true function. However, if the true function is non-monotonic, the RSE fitness to that true function may be very poor.

IV. RESULTS

A 3-level full factorial design was used to conduct the experiments using the C-MAPSS simulation platform. A 3-level design can be used to investigate whether any nonlinear relationship exists between the response variable and the factors.

A. HPT creep progression model

Since the fault progression model is obtained under the assumption that the other subsystems are healthy, it requires much fewer data points (just one variable is changing). A simple regression model was used to explore the relationship. It was observed that the following equation explains well the relation between the response variable (creep damage caused to the HPT blades during the climb phase) and the HPT fault index, assuming other subsystems are healthy.

\[ Y = 10^{-1}(26.0 + 2.3FI_{HPT} + 0.18(FI_{HPT})^2) \]

Though, the actual values of coefficients in this equation will vary by changing the operating conditions, yet it provides an important piece of information about the structure of the model, irrespective of operating conditions; the since the linear coefficient is much larger than the quadratic coefficient, a linear fault progression model for creep damage will suffice.

B. Fault propagation model

To investigate fault propagation parameters (the effects of health deterioration of other subsystems on another life limiting failure mode), DoE methods were used for 2 cases. One set of experiments was carried out to investigate the effects of LPC fault on HPT creep damage (Table 2), and another set to investigate the effects of HPC fault on HPT creep damage (Table 3). The simulation results were then exported to JMP (a statistical analysis software by the SAS institute. For both the cases (LPC fault and HPC fault), the following aspects of the data were analyzed.

Main effects, also called average main effects, explain how the response (creep damage) changes on the average due to change in level of one of the factors.

Interaction effects determine whether the relation between the response and one of the factor is dependent on the other factors as well.
C. LPC-HPT fault propagation

Based on data in the Table 2, the following RSE model was obtained.

\[ Y = 10^{-3} (25.4 + 0.44 F_{lpc} + 3.52 F_{hpt} + 0.021 F_{lpc} \cdot F_{hpt}) , \]

where \( Y \) is the creep damage in percentage (100% implies complete life cycle of the engine).

The main effect parameters in the model reveal that there does not exist a significant effect of LPC fault on creep damage. The interaction effect parameter shows that creep damage caused by the LPC fault does not vary significantly by the HPT fault level.

D. HPC-HPT fault propagation

Similarly using Table 3 data, the following RSE model was derived.

\[ Y = 10^{-3} (26.64 + 5.0 F_{hpc} + 2.99 F_{hpt} - 0.23 F_{hpc} \cdot F_{hpt} ) . \]

This RSE shows that HPC fault significantly affects creep damage, even more than HPT fault itself.

V. CONCLUSIONS

We presented a methodology to analyze the interactions between the health of various subsystems. The application domain was turbofan engine of a commercial aircraft, and the specific fault mode was creep damage in HPT blades. It was observed that in the absence of health deterioration in other subsystems, creep damage in HPT evolves in a linear fashion. It was also observed that LPC fault/deterioration has a small effect, while HPC fault/deterioration has an extremely large effect on HPT creep damage (Fig. 4).

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REFERENCES


**BIOGRAPHY**

Manzar Abbas earned the B.E. degree from the National University of Sciences and Technology (NUST), Pakistan in 1999 and the Masters of Electrical Engineering from the Georgia Institute of Technology in 2007. He joined intelligent control systems laboratory (ICSL) in summer 2005 and is currently a Ph.D. candidate in Electrical Engineering at the Georgia Institute of Technology. In the past, he carried out applied research in the areas of fault diagnostics and failure prognostics of electrical, electrochemical, electromechanical and electronics systems. Currently, he is working on developing a methodology to analyze fault propagation from one subsystem to the other subsystems with a specific focus on turbo machinery.

George Vachtsevanos is a Professor Emeritus of Electrical and Computer Engineering at the Georgia Institute of Technology. He was awarded a B.E.E. degree from the City College of New York in 1962, a M.E.E. degree from New York University in 1963 and the Ph.D. degree in Electrical Engineering from the City University of New York in 1970. He directs the Intelligent Control Systems laboratory at Georgia Tech where faculty and students are conducting research in intelligent control, neurotechnology and cardiology, fault diagnosis and prognosis of large-scale dynamical systems and control technologies for Unmanned Aerial Vehicles. His work is funded by government agencies and industry. He has published over 240 technical papers and is a senior member of IEEE. Dr. Vachtsevanos was awarded the IEEE Control Systems Magazine Outstanding Paper Award for the years 2002-2003 (with L. Wills and B. Heck). He was also awarded the 2002-2003 Georgia Tech School of Electrical and Computer Engineering Distinguished Professor Award and the 2003-2004 Georgia Institute of Technology Outstanding Interdisciplinary Activities Award.