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How In-Service Experience Informs Design Modifications: A Case Study in Aero Engines

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Abstract

This research is triggered by a fundamental shift that is occurring in the manufacture and marketing of aero engines for commercial and defence purposes, away from the selling of products to the provision of services. Under the emerging 'power by the hour' paradigm, aero engines are effectively leased to the airlines, with the manufacturing company remaining responsible for their maintenance and repair throughout their service life. This has triggered a major re-assessment of the design of aero engines to reduce their overall life-cycle costs, while maintaining performance efficiency. The important aims of our ongoing research are: firstly to understand the current flows of in-service information to designers; secondly to understand the information requirements of designers about in-service issues; thirdly to develop the most appropriate theories and methods to support designers in their new task. This paper presents the results of the initial phase of an ongoing research project, which is addressing the first aim of the research, and analyses a sample of service documents currently used by the manufacturing company. Within this sample, a distribution pattern of failure mechanisms across turbines, compressors and combustion chambers has been identified, and the prominent design changes to resolve those failure mechanisms and their benefits are noted. The relationships between some of the parameters are presented, e.g. the type of design changes made to address a particular failure mechanism, and the typical benefits of a particular design change.

Keywords: aero engine, service experience, failure mechanism, design change

1. Introduction

A fundamental shift is occurring throughout the aerospace industry (including our collaborating aerospace company) away from the selling of products to the provision of services. The collaborating company is involved in high-technology aerospace products. The Aerospace Group in the Company is involved in the design, manufacture and provision of service support for Aero Engines. The company is now increasingly responsible for the maintenance and servicing of its aero engines on a 'power by the hour' basis, under which working aero engines are effectively leased to the airlines. This has stimulated a new set of requirements in the design of future aero engines, including long and predictable service intervals, ease of service and high reliability [1].

Essential to the long-term success of businesses competing in this emerging global environment is the creation of new products and services, integrated into a single commercial package. In the aerospace sector it is already standard design practice to utilise the experience gained from past projects: in-service information related to the failures and malfunctions of existing aero engines is inspected and analysed, to avoid these failures in future designs. A flow of information from the service domain back to designers is thus crucial in reducing in-service failures, and in cutting down maintenance costs. If appropriate knowledge about the maintenance of existing products can also be successfully fed back to the designers of new products, then many of these new challenges can be addressed at the design stage.

This paper presents the results of the initial phase of an ongoing research project. As a part of this research, a number of exiting documents containing service information have been analysed. The information in these documents relates to the requirements that should be considered by designers while carrying out the designs of new aero engines, based on the lessons learned from the service experience of existing engines. These documents summarise the various types of failure mechanisms occurring in the existing aero engines, design changes in the next generation of engines to eliminate those failure mechanisms, and the benefits of the proposed changes.

The outline of the paper is as follows. Section 2 presents the relevant literature. Section 3 describes the service documents used in the analysis, along with the method used to analyse them. Section 4 explains the various parameters described in the documents, including the various failure mechanisms and their distribution across turbines, compressors and combustion chambers. The section also lists design changes carried out to resolve those failure mechanisms, and their benefits. Section 5 provides relationships between some of the parameters, e.g. the type of design changes made to address a particular failure mechanism, and the typical benefits of a particular design change. The conclusions are presented in Section 6.

2. Literature review

The maintenance cost of engines is crucial to airlines, as it forms a significant part of the total operating cost of an aircraft. The cost of spares, and the service life of critical components, are important factors in those maintenances costs [2]. The body of information about the failure modes of different components allows designers to improve the design of new engines. James [3] observes that the failure of an engineering component or structure can be due to incomplete, inaccurate, or inappropriate information related to one or more stages of the design process, or to poor management of the design process itself. The manifestation and severity of failure often depends on which stages of the total design process have not been managed properly. Insufficient understanding of the requirements of the system may lead to failures. It is clear that the information and knowledge about the various service issues play an important role in the design.

The literature suggests the importance of service experience in improving the design of the next generation of products. Alonso-Rasgado et al [4] highlight the importance of service data collection and storage, with reference to the design of functional that is total care products. Dahl et al [5] highlight the importance of operations and maintenance information in the design in the construction industry. Thompson [6] describes the importance of information related to maintenance for informing design decisions: operating records, interviews with maintenance personnel are a vital source of information for the designers. Sander and Brombacher [7] conducted a study of high-volume consumer products and conclude that, in order to improve future products, the entire relevant service experience from the previous products should be evaluated, stored and used.

The causes behind product failures are important in the design of the next generation of products. Petkova [8] studied the field feedback (flow of in-service information back to the manufacturing company) in the consumer electronics industry. She states: “If a company wants to improve its product quality, it should look first and in particular for the root causes of product failures.” The paucity of literature on field feedback has been highlighted. She has classified the field information into: engineering information which is necessary to detect the root-cause of a product failure and statistical information, i.e. quantitative information about the frequency of product failures. The statistical information provides an indication about the overall performance of a product but in contrast to engineering information, it does not provide any details about the modes of failure. Harrison [9] discusses the elements of the process, problems and successes in the deployment of ‘Design for Service’ for the Trent 1000 aero engine, designed for the Boeing 787. He lists some of the significant operator cost drivers such as: range and payload, safety, schedule reliability, life cycle fuel burn and engine overhaul. He mentions the following concepts, which can address all of the above drivers positively:

- understanding the engine’s deterioration mechanisms;
- controlling their rate of occurrence and impact;
- ensuring effective and low cost restoration of capability at overhaul.

Service experience facilitates the prediction of the reliability and availability of products; and it plays a significant role in the optimization of maintenance procedures. Norman [10] states that reliability or availability forecasts can be based on past operating experience. These forecasts will be precise if the sample size is large enough, and unbiased. Jones and Hayes [11] describe the importance of the collection of field failure information throughout the life of a product and of analysing this data to evaluate the reliability of the product in the field. This helps improve the reliability of the next generation of products. Sandtorv et al [12] have presented the results and knowledge gained from a project called OREDA (Offshore REliability DAta). The application of the OREDA data was in the risk and availability studies in the early concept and engineering phases of an offshore development, and also in maintenance optimization.

3. Service documents and analysis method

As part of this research, a number of service documents containing service information have been analysed. Information in these documents relates to the requirements that should be considered by designers while carrying out the design of new aero engines, so that all the lessons learnt from past experience (including engines that are currently in service) can be applied. In addition, the documents describe the design changes proposed for the next generation of engines to eliminate the failure mechanisms, and the anticipated benefits of those design changes.

The documents used in the analysis were created through meetings between designers and service engineers. The collaborating company calls these documents ‘strategy sheets’. They are based partly on the experience gained from aero engines already in service and partly on the engineering assessment of failure mechanisms that could theoretically occur if not addressed in the design phase. In-service experience from three different aero engines was covered in the documents that we analysed; figure 1 shows the years of service experience with these engines.

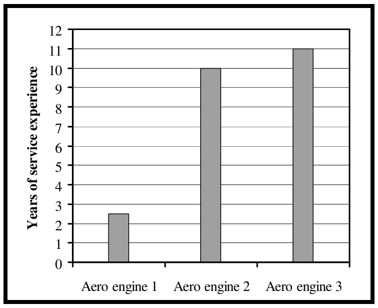

Figure 1: Years of service experience with aero engines 1, 2 and 3

In total, ten strategy sheets were provided. Out of these ten, five related to turbine modules, three to compressor modules and two to combustion chambers. Included in the ten strategy sheets are a total of 93 cases. A 'case' is a failure mechanism in one or more of the existing aero engines together with the design changes in the next generation of aero engines to eliminate the failure mechanisms and the anticipated benefits of those changes. Out of these 93 cases, 52 are related to turbines, 26 to compressors and 15 to combustion chambers. Table 1 presents the distribution of these cases amongst the components within the three modules covered by the strategy sheets.

In our analysis, there were no presumed categories; instead, different categories were devised during the analysis. The main parameters described in the strategy sheets were identified along with their commonalities; e.g. in 'design changes', all changes involving material change were grouped together. The relations of some parameters with other parameters were identified.

Table 1: Distribution of cases

Strategy Sheet	Name of the component	Number of cases
1	Combustion Case	7
2	Combustion Liner	8
3	HPT NGV (High pressure turbine - Nozzle guide vane)	8
4	HPT Blade	10
5	IPT (Intermediate pressure turbine) NGV	14
6	IPC (Intermediate pressure compressor) Blade Retention Devices	14
7	IPC Blades	7
8	IPC Variable Vane Mechanism	5
9	IPT Seal Segment	5
10	IPT Blade	15
		Total = 93

4. Analysis of the service documents

The various parameters in the analysed service documents are failure mechanisms, design changes and benefits of the design changes.

4.1 Failure Mechanisms

Failure modes are the observable manners in which a component fails [13]. Failure modes provide the way in which a component fails [14, 15]. The failure mechanism causes the failure mode, which in turn causes the failure effect [13]. Failure mechanisms provide the actual physical processes leading to a failure [14]. Table 2 shows examples of failure mechanisms, modes, and effects. Tsai et al [16] highlight two types of mechanisms that cause failure modes in mechanical systems such as extrinsic problems of systems (e.g. poor lubrication, bad connection due to loosened parts, etc.); and intrinsic damages (e.g. repeated cycles resulting in mechanical fatigue, contact stress leading to excessive wear of parts, the chemical change on surfaces weakens materials (corrosion), etc.). Tumer et al [17] state that a standard taxonomy describing failures can help designers in achieving appropriate design solutions. They propose a taxonomy which provides a physics-based explanation of failure modes. A physics-based description of failures is necessary to understand the true nature of a failure.

Table 2: Examples of failure mechanisms, failure modes, and failure effects [Ebeling, 1997]

Failure mechanism	Failure mode	Failure effect
Corrosion	Failure in tank wall seam	Tank rupture
Manufacturing defect in casing	Leaking battery	Failure of flashlight to light
Contamination (dust and dirt)	Loss of contact	Circuit board failure
Evaporation	Filament breaking	Light bulb burnout

In the case of aero engines, various failure mechanisms can occur. Figure 2 gives the number of occurrences of different failure mechanisms that occurred more than once in the documents.

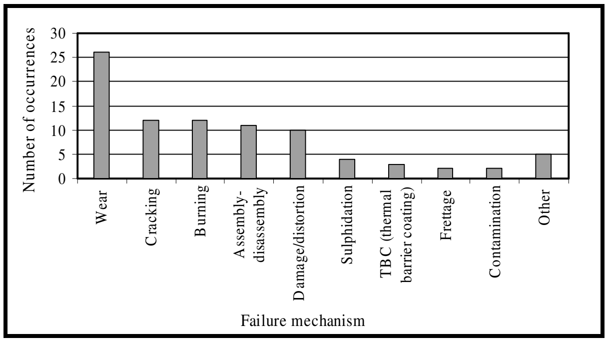

Figure 2: Occurrences of various failure mechanisms

A total of 15 types of failure mechanism are identified in the 93 cases. Six failure mechanisms (40% of the total) occurred only once. In one case, combination of failure mechanisms is seen, namely frettage and fracture. In some cases, the description of the failure mechanism is very unclear. In these cases the failure mechanism is labeled ‘other’.

Table 3 shows the distribution of various failure mechanisms across turbines, compressors and combustion chambers. It also gives percentages of occurrences of the different failure mechanisms for each of these major assemblies. The ‘other’ failure mechanisms are not considered in this Table.

Table 3: Distribution of failure mechanism occurrences across turbines, compressors and combustion chambers

Failure mechanism	Total number of occurrences (More than one)	Turbine		Compressor		Combustion chamber	
		Cases	% of the cases seen in turbine	Cases	% of the cases seen in compressor	Cases	% of the cases seen in combustion chamber
Wear	26	15	29	7	27	4	27
Cracking	12	8	15	0	0	4	27
Burning	12	9	17	1	4	2	13
Assembly disassembly	11	3	6	7	27	1	7
Damage/distortion	10	3	6	7	27	0	0
Sulphidation	4	4	8	0	0	0	0
TBC loss	3	2	4	0	0	1	7
Frettage	2	0	0	1	4	1	7
Contamination	2	2	4	0	0	0	0
Total	82	46		23		13	

Table 4 shows the distribution of failure mechanisms that appear only once across turbines, compressors and combustion chambers.

Table 4: Distribution of failure mechanisms, occurring only once, across turbines, compressors and combustion chambers

Assembly	Failure mechanism
Turbine	Blockage
	Creep
Compressor	Frettage, Fracture
	Seizure
Combustion chamber	Galling
	Porosity

From Tables 3 and 4, the following points can be inferred:

- Cracking is observed only in turbines and combustion chambers;
- The highest percentage of cracking is observed in combustion chambers, followed by turbines;
- Almost the same percentage of wear is observed in turbines, compressors and combustion chambers.
- Wear, damage/distortion and failure mechanisms related to assembly-disassembly (e.g. difficult to disengage, incorrect fitment, not fully engaged, etc.) are seen prominently in compressors;
- Sulphidation and contamination are seen only in turbines.

It is important to note that these inferences apply only to the documents that we have analysed so far, which cover only three modules, and which represent only a small sample of the total number of such documents generated by our collaborating company.

4.2 Design Changes

For some of the failure mechanisms, design changes in the next generation of aero engines are also described in the documents. These design changes are of several different types. The prominent design changes are:

- geometry change;
- material change;
- part deletion;
- manufacturing improvement.

Some design changes are initiated by identifying the cause behind the failure mechanism, and these were described explicitly in the documents. Such a design change is termed a cause-related one, e.g. a design change to eliminate an area of stress concentration that had caused cracking.

4.3 Design Benefits

The documents describe the benefits of the design changes. Several types of benefit are seen. The most common design benefits are:

- an improvement in some parameter, e.g. increased impact resistance due to an increase in a particular dimension, or improved oxidation resistance;
- failure mechanism elimination;
- the reduced likelihood of a failure mechanism occurring, e.g. lowering the stress concentration reduces the probability of crack initiation;
- an increased number of cycles in the life of the component;
- a reduction in repair cost;
- improved aspects of a component’s total lifecycle, e.g. becoming easier to manufacture or assemble.

5. Relations between parameters

Relationships between failure mechanisms and the related design changes were identified. Some relationships between design changes and the related design benefits were also observed.

5.1 Failure Mechanism - Design Change

In some cases, a clear link can be observed between failure mechanisms and the corresponding design changes (see Figure 3). Manufacturing-related design changes are the results of failure mechanisms related to assembly and disassembly. Geometry-related changes are the results of cracking and wear. Material-related changes are the results of sulphidation and burning. In other cases, no consistent links were identified.

		Design change		
		Manufacturing improvement	Geometry change	Material change
Failure mechanism	Assembly-disassembly	▨		
	Burning			▨
	Cracking		▨	
	Wear		▨	
	Sulphidation			▨

Figure 3: Links between failure mechanism and design change

5.2 Design Change - Design Benefit

In some cases a clear link was observed between design changes and corresponding benefits (see Figure 4). Geometry-related design changes often lead to an improvement in some variable. Material-related deign changes tend to increase the number of operating cycles and eliminate failure mechanisms. Design changes deleting a part typically eliminate a failure mechanism altogether. In other cases, no particular links were observed.

		Design benefit		
		Improvement in some variable	Increased number of cycles	Mechanism elimination
Design change	Geometry	▨		
	Material		▨	▨
	Part deletion			▨

Figure 4: Links between design changes and resulting benefits

6. Conclusions and further work

Analysis of a sample of the collaborating company's "strategy sheets" has provided valuable insights into some of the failure mechanisms seen in aero engines. Specifically, a pattern of failure mechanisms is seen across turbines, compressors and combustion chambers. Wear, cracking, burning, damage/distortion and failure mechanisms related to assembly/disassembly are prominent failure mechanisms in one or more of these modules (though, of course, these failure mechanisms have not all actually occurred in recent engines). 40% of failure mechanisms were seen only once in the documents we analysed. Burning, wear, cracking are prominent in turbines and combustion chambers. Wear, damage, distortion and failure mechanisms related to assembly or disassembly are prominent in compressors. The majority of the design changes implemented to resolve these failure mechanisms are related to geometry change, and material change. Major design benefits resulting from these design changes are: an improvement in some parameter, the total elimination of a failure mechanism, or the reduced probability of a mechanism occurring. A pattern of links has been identified between failure mechanisms and design changes, and between design changes and design benefits.

The above findings are based on the analysis of a small sample of documents, so may not be fully representative; a further project to analyse a larger sample of strategy sheets, using information extraction from text [18], is therefore being planned. Other work, to identify the knowledge required for designers to create parts which will perform reliably in service, is also in progress.

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