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Application of physical failure models to enable usage and load based maintenance

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ABSTRACT

The efficiency of a preventive maintenance process largely depends on the ability to predict the replacement intervals of components. Considering the actual usage of the system increases the accuracy of this prediction. The present paper proposes two new maintenance concepts, that combine the benefits of traditional static concepts and condition based maintenance. These new concepts, usage based maintenance and load based maintenance, apply usage or load parameters that are monitored during service to perform a physical model-based assessment of the system condition. The new concepts are positioned within the range of existing maintenance concepts. Also, the role of physical models in maintenance modelling in general is explained and the origin of uncertainty in the predicted service life is discussed. Moreover, it is demonstrated how the monitoring of usage, loads or condition can reduce this uncertainty and increase the service life, by extending existing work in this field. Finally, the different concepts are applied to a gas turbine blade case study to illustrate the benefits of the proposed concepts.

1. Introduction

Maintenance of technologically advanced systems is costly due to the high costs of the spare parts and the required labour hours. On the other hand, maintenance is of vital importance to keep the system availability at an acceptable level. Especially in a military context, availability has a high priority, which often leads to conservative maintenance intervals and consequential high maintenance costs.

Maintenance strategies can be divided into two basic classes [1]. In *corrective* strategies, parts are only replaced or repaired after they have failed. This means that the part's service life is fully utilized, but failure can occur at any moment, which may decrease the system's availability considerably or may cause additional damage in other parts. A *preventive* maintenance strategy aims to prevent failure by replacing or repairing the parts before they fail. In that way, maintenance activities can be planned at suitable moments such that they do not strongly affect the availability of the system. However, since the actual moment of failure is hard to predict, many parts are replaced far before the end of their service life, which increases the maintenance costs considerably.

The choice for one of these strategies depends on the part or system under consideration. For parts that can easily be replaced and whose failure is not critical, corrective maintenance is the optimal procedure. On the other hand, for critical parts in complex systems, like e.g. turbine blades in a gas turbine engine, preventive maintenance is more suitable. In a military environment, reliability is very important and many parts and systems are denoted critical. Therefore, preventive maintenance is common practice in this context.

The key issue of the preventive methods is the determination of the maintenance intervals, i.e. the timing of the various maintenance activities like repair or replacement of parts. If the intervals are too large, failure will occur, while too small intervals lead to overmaintenance: the service life of parts is only partially utilized and the amount of labour hours is unacceptably high. However, the best compromise between these two counteracting processes is not the same for every part or system. Again, the criticality of the component determines whether the interval tends to the *effective* (short) or the *efficient* (long) side. In the former case, where components are critical, large safety factors are applied to avoid failure. The magnitude of these factors will be determined on a statistical basis in Section 3 of this paper.

In the next section, the available literature on the different maintenance concepts will be reviewed and categorized. Two original maintenance concepts will then be introduced and positioned relative to existing concepts. The remainder of this paper then quantifies the benefits of the proposed concepts, both theoretically and in a gas turbine blade case study.

2. Maintenance concepts

For the determination of the maintenance intervals, several approaches can be followed. In Fig. 1 a categorization of these

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concepts is proposed, using three criteria: the moment in the system life cycle at which the intervals are determined, the way in which the system condition is assessed during the service life and the prognostic approach that is followed. In the present section these criteria will be discussed and existing concepts and methods from literature will be categorized. After that, the new concepts of usage and load based maintenance (UBM and LBM), as indicated by the red blocks (and no. 5) in Fig. 1, will be introduced and the contents of the present paper will be outlined.

2.1. Moment in life cycle

The first criterion used in Fig. 1 is the moment in the life cycle at which the intervals are determined. Traditionally, the manufacturer quantifies the interval during the design phase of the system or component, using assumptions on the future usage. This leads to a *static* concept in which fixed intervals are applied during the complete service life of the system, disregarding any variations in usage. More recently, *dynamic* maintenance concepts are being developed, where the actual usage or system degradation is taken into account and the required maintenance intervals are regularly updated or even fully determined during the service life. The latter concept can be applied in a *passive* way, where components are replaced or repaired shortly after the condition of the system reaches a critical level. In a more *proactive* variant, a prediction is made for the remaining useful life after every condition assessment, which provides more time to plan and prepare the repair or replacement.

2.2. Condition assessment

The second criterion is the method used to determine the system condition during the service life. Obviously, for the static concepts (1 and 2 in Fig. 1) no condition assessment is performed at all, since the intervals are fully determined before the system enters service. For the dynamic concepts there are currently two approaches.

The most commonly used method is condition monitoring (concept 3 in Fig. 1), where appropriate sensors or inspection techniques are used to asses the system condition [2–5]. This can be done in a direct or indirect manner. The indirect method monitors performance parameters, like the flow in a pump, and applies these as an indication for the condition of the system. In the direct method, sensors are installed that directly monitor the condition of the system or component. Examples are delamination sensors in composite structures, crack length sensors, sensors to detect metal particles in lubrication oil and vibration monitoring systems. The difference between indirect and direct methods has been described by Veldman et al. [6], denoting the methods as 'based on process data' and 'based on failure data', respectively. The difference between physical model based and purely mathematical (experience based) methods to predict failure, as will be discussed in the next subsection on prognostics, is recognized in [6] as a second characteristic of CBM methods. The methods are denoted 'analytical modelling' and 'statistical modelling'. Saranga [7] also distinguishes indirect and direct condition parameters, denoted by relevant condition *indicators* (*RCI*) and *predictors* (*RCP*), respectively. Finally, several papers devoted to cost optimization [8–11] and availability [12] under a condition based maintenance strategy are available.

An alternative method to estimate the system condition is based on the correlation between certain usage profiles and the resulting system degradation. This method is often applied in rotorcraft health and usage monitoring systems (HUMS), where it is called flight regime recognition [13,14]. For each flight regime, past experience enables the attribution of a relative damage severity. By monitoring the usage, both the present condition and

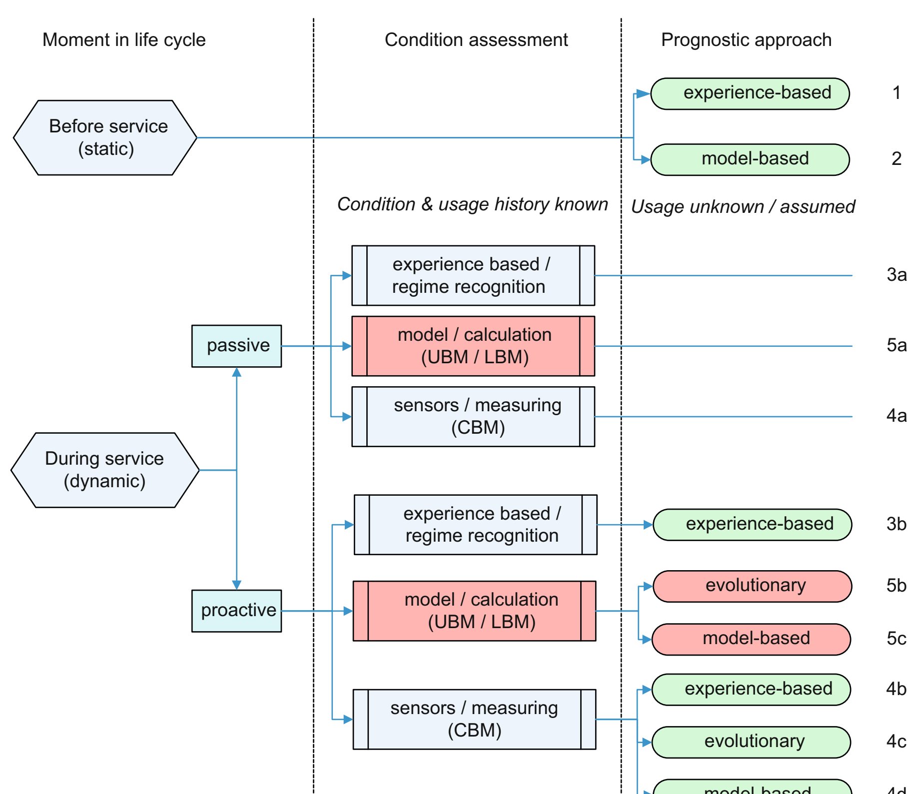

Fig. 1. Categorization of preventive maintenance concepts.