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Performance-based health monitoring, diagnostics and prognostics for condition-based maintenance of gas turbines: A review

Mohammadreza Tahan [a], Elias Tsoutsanis [b], Masdi Muhammad [a,*], Z.A. Abdul Karim [a]

[a] Department of Mechanical Engineering, Universiti Teknologi PETRONAS, 32610 Bandar Seri Iskandar, Malaysia
[b] School of Engineering, Emirates Aviation University, Dubai, United Arab Emirates

HIGHLIGHTS

- A systematic review of gas turbine engine monitoring approaches is presented.
- The inception of engine diagnostics and prognostics and their evolution are reviewed.
- Causes of engine deterioration to facilitate fault identification are discussed.
- Techniques for engine model adaptation through component map tunings are summarized.

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ABSTRACT

With the privatization and intense competition that characterize the volatile energy sector, the gas turbine industry currently faces new challenges of increasing operational flexibility, reducing operating costs, improving reliability and availability while mitigating the environmental impact. In this complex, changing sector, the gas turbine community could address a set of these challenges by further development of high fidelity, more accurate and computationally efficient engine health assessment, diagnostic and prognostic systems. Recent studies have shown that engine gas-path performance monitoring still remains the cornerstone for making informed decisions in operation and maintenance of gas turbines. This paper offers a systematic review of recently developed engine performance monitoring, diagnostic and prognostic techniques. The inception of performance monitoring and its evolution over time, techniques used to establish a high-quality dataset using engine model performance adaptation, and effects of computationally intelligent techniques on promoting the implementation of engine fault diagnosis are reviewed. Moreover, recent developments in prognostics techniques designed to enhance the maintenance decision-making scheme and main causes of gas turbine performance deterioration are discussed to facilitate the fault identification module. The article aims to organize, evaluate and identify patterns and trends in the literature as well as recognize research gaps and recommend new research areas in the field of gas turbine performance-based monitoring. The presented insightful concepts provide experts, students or novice researchers and decision-makers working in the area of gas turbine engines with the state of the art for performance-based condition monitoring.

1. Introduction

The gas turbine is one of the main sources of power for many applications such as civil and military aircraft, naval and commercial ships, electricity production, gas compression, and high-scale pumping services. The deep penetration of renewables into the energy mix has amplified the need for gas turbines to operate more efficiently and in partnership with renewable energy sources such that energy is produced in an environmentally friendly manner. In addition, for many of the world's largest manufacturers, aftermarket service and parts operations are essential to their business. For example, Rolls-Royce has more than 14,000 aerospace engines in service, operated by more than 500 airlines and powering more than 5.5 million commercial flights per year and the company's service and part business revenue is about 55% of the approximately US$11 billion total revenues [1]. Within this context, sev-

* Corresponding author.
E-mail address: masdimuhammad@utp.edu.my (M. Muhammad).

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eral technical challenges with respect to the operation and lifecycle cost of gas turbines must be addressed to efficiently implement this technology in a volatile energy market. It is well known that the development and implementation of a robust, efficient and flexible maintenance strategy significantly improves the reliability and availability of gas turbine assets and, as a result, decreases the number of unpredicted breakdowns, operating costs, and downtime. The main factors affecting gas turbine maintenance planning are shown in Fig. 1. It is clear from Fig. 1 that there are numerous trade-offs among environmental, technological, economic and operational factors that establish a successful maintenance and operational strategy of gas turbine assets [2].

In recent years, the gas turbine manufacturers have transformed into modern digital businesses by converging the industrial equipment, data and the internet into a platform that enables the optimization of asset monitoring and management [3]. Examples of such technologies are GE's Predix and Digital Twin where in the case of gas turbines numerous fleets of engines across the globe are simulated, monitored and analyzed as seen from Fig. 2.

The analytics methods, which are based on banks of data containing the operational and simulation history of the engines, are employed for improving the gas turbine operators understanding for these complex nonlinear machines. Therefore, the maintenance actions are based on informed judgments for the assets in order to maximize their profitability, reduce life cycle costs and improve reliability and availability. It has been recently demonstrated that the implementation of such digital platform for analytics and optimization can have significant savings in the Oil & Gas and the Airline sectors to name a few. For instance, in the airline sector, both Southwest [4] and Quantas [5] airlines are in the process of saving millions of dollars in fuel cost by a data-crunching partnership with the engine manufacturers. On the other hand in the O&G sector [6], the savings attributed by implementing this digital platform is in the order of billions per year taking into account that an unscheduled downtime for an LNG facility and an offshore platform cost $25 million and $7 million per day, respectively. The opportunity for developing and adopting such a digital platform based on engine models, condition monitoring, diagnostics and prognostics solutions is spearheading the transformation of the conventional industrial environment into its digital era with huge prospects for the availability and reliability of equipment.

It is generally accepted [2,7–9] that condition-based maintenance (CBM) is an effective method for enhancing the machinery maintenance strategy and shifting from classical "fail and fix" practices to a "predict and prevent" methodology. As summarized in Table 1, while reactive-based corrective maintenance is performed just upon failure or error happening in the system, preventive maintenance employs the statistical machine information and operational experience to schedule successive overhauls in order to prevent unexpected failure in the system. However, to improve the reliability and availability of the system, in predictive maintenance, the operating conditions of the equipment are continuously monitored to detect the need for real-time maintenance. Consequently, the continuous development and implementation of condition monitoring, diagnostic and prognostics methods can significantly reduce both the economic losses caused by system breakdown and the costs attributed to unnecessary repair and replacement of components.

Generally, the informed judgment that supports any maintenance decision is the objective of the CBM, the success of which relies on two related processes described as follows:

(A) Diagnostics is the process of determining the health status and the equipment deterioration using information delivered by the condition-monitoring system [11]. The main objectives of diagnostics are: (i) fault detection, which indicates that an undesirable event is imminent; (ii) fault isolation, which locates the faulty component; and (iii) fault identification, which aids in determining the root cause of the fault.
(B) Prognostics is the ability to forecast the evolution of engine deterioration [12]. The two major objectives of prognostics are: (i) forecasting the impending failures and (ii) estimating the remaining useful life of the engine.

As discussed by Puggina et al. [13], the implementation of proper diagnostic and prognostic approaches has several merits mainly including tuning components costs and performing predictive maintenance actions, optimizing shop visits and providing

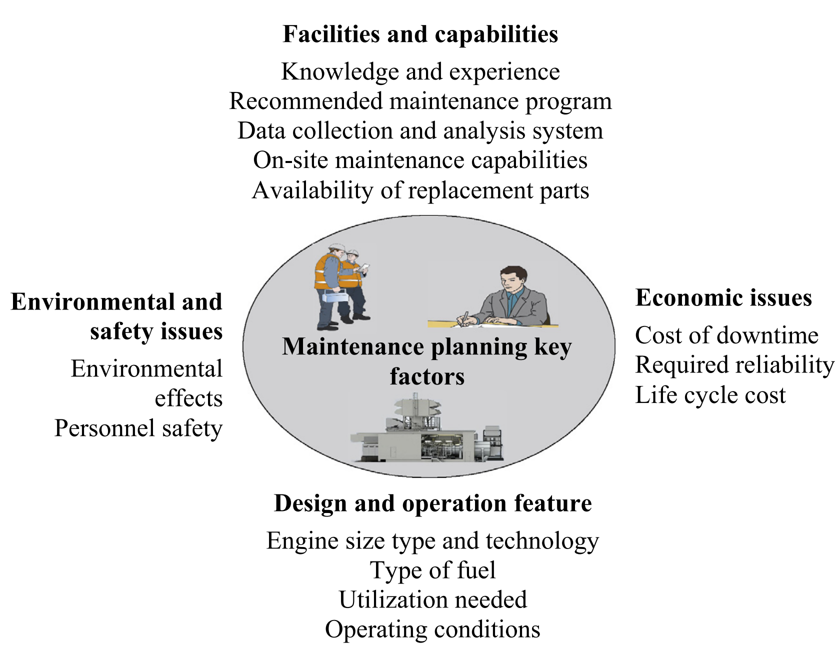

Fig. 1. Principal factors that affect gas turbine maintenance planning [2].