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Sequential pattern mining applied to aeroengine condition monitoring with uncertain health data

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ABSTRACT

Numerical algorithms that can assess Engine Health Monitoring (EHM) data in aeroengines are influenced by the high level of uncertainty inherent to gas path measurements and engine-to-engine variability. Among them, fuzzy rule-based techniques have been successfully used due to their robustness towards noisy signals and their capability to learn human-readable rules from data. These techniques are useful in detecting the presence of certain types of abnormal events or general engine deterioration, through the identification of specific combinations of EHM signals associated with these specific cases. However, there are also other types of engine events that manifest themselves as an ordered sequence of otherwise normal combinations of the EHM signals. These combinations are dismissed when considered in isolation as the current existing techniques cannot assess them. In this paper it is proposed to use sequence mining techniques in order to obtain fuzzy rules from uncertain EHM data which can in turn be used to identify the cases where an engine event is determined as a sequence of otherwise normal combinations of EHM signals. The results are subsequently tested on a representative sample of aeroengine data.

1. Introduction

The main use of engine data is to control and manage the engine. This is to monitor the engine parameters in order to avoid running the engine under undesired conditions. The built-in system knowledge within the engine and aircraft is configured to trigger alerts to highlight the need for pilot or maintenance action or to shut down the engine if a significant condition would be encountered. In addition, the engine data is also monitored for its development over time, this is what is understood as Engine Health Monitoring (EHM) (Sundaram et al., 2009).

There have been multiple methods of EHM data assessment developed over time. The most common methods are based around Gas Path Analysis (GPA), where pressures, temperatures, rotation speeds, etc., are monitored in relation with the inlet and control parameters (atmospheric conditions, fuel consumption, power turbine rotation speed, etc.). GPA methods consider the variability of the engine parameters based on the engines' internal damage and deterioration (Kestner et al., 2011; Yepifanov and Loboda, 2003).

1.1. Notation

The typical locations in a two shaft high bypass ratio turbo fan where EHM data is sampled are shown in Fig. 1 (Sforza, 2012). In this type of engine, the thrust is provided by the air compressed by the fan blades and pushed through the engine bypass. The air pushed through the core of the engine is solely used to turn the fan in the most efficient way possible. This is, the air is compressed by the high pressure compressor (HPC) so that the optimum conditions are reached within the combustion chamber to subsequently turn the high pressure turbine (HPT) to maintain the high pressure (HP) system and subsequently turn the low pressure turbine (LPT) which moves the fan to produce the engine thrust.

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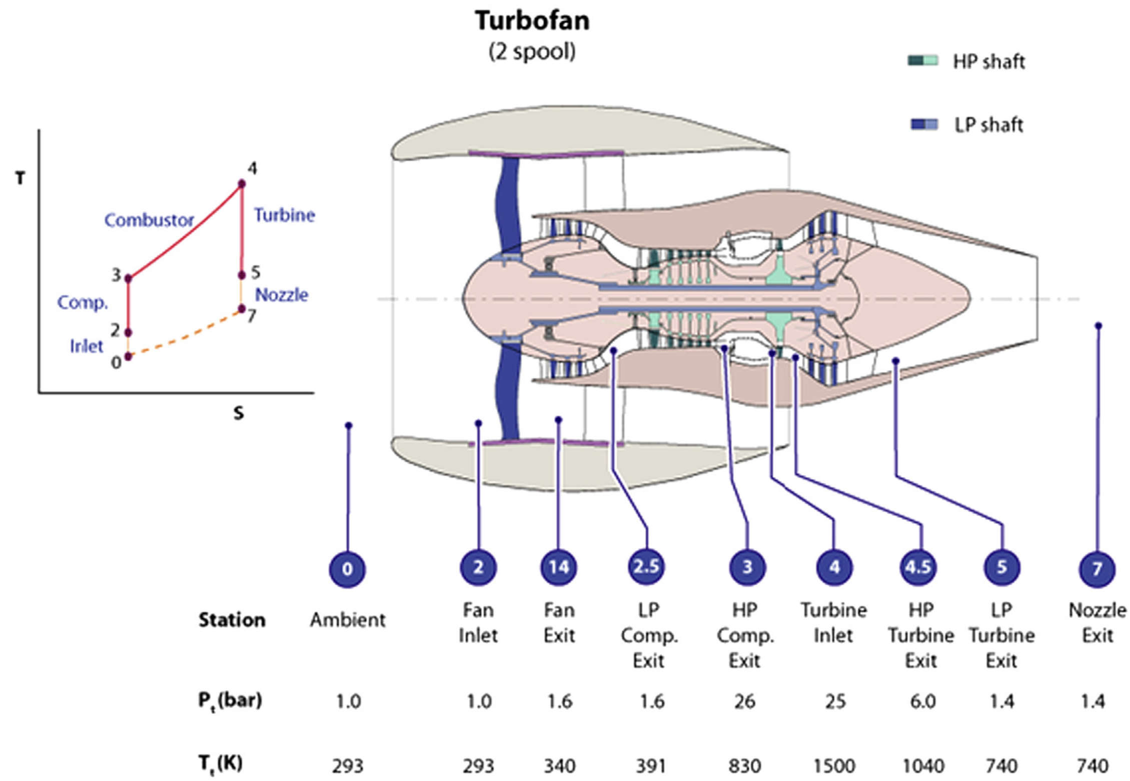

Fig. 1. Typical two shaft high bypass ratio turbo fan, and Temperature (*T*)–Entropy (*S*) diagram of the Turbojet cycle. The compressor raises the combustor inlet temperature, increasing the cycle area and the thermal efficiency.

The main stations depicted in Fig. 1 follow the most commonly used numbering convention (SAE, 2014). Although single digits are used to define the main stations, double digits are used to define interim positions. The first digit defines the main station whilst the second defines an interim position. Therefore, for example Station 2 may also be known as Station 20 or Station 3 may also be defined as Station 30. Depending on the context these may be used indifferently and therefore at Station 2 the P2/T2 probe is used to measure these variables whilst the temperatures and pressures at Station 3 are known as P30 and T30.

- *Station* 0: The measurements at this position are used to determine the ambient or external conditions. These are generally measured by the aircraft.
- *Station* 2: Due to the design of the engine intake the temperature and pressure at Station 2 are different from those of Station 0 and are more representative of the actual engine intake conditions which will be in turn used as reference by the controls system. The main variables at this station are P2 and T2.
- *Station* 14: This is used to determine the actual efficiency of the fan, as it solely sees the section of air compressed by the fan which runs through the engine bypass. No significant measurements are taken at this position, as the engine thrust may be calculated based on the engine design knowledge from the Engine Pressure Ratio (EPR) or the N1 speed (speed of the LP system) defined below.
- *Station* 25: This is the entry to the HPC. Depending on the engine design a booster or an Intermediate Pressure Compressor (IPC) may also be associated with the low pressure (LP) system. Station 25 is therefore defined as the entry to the HPC and not the exit of the fan.
- *Station* 3: This is the HPC exit and the entry into the combustion system. The conditions at this point are key for the correct functioning of the engine. The main variables measured at this station are P30 and T30.
- *Station* 4: This is the combustion chamber exit and HPT entry. The temperature at this point is one of the main engine parameters. T4 may also be known as Turbine Gas Temperature (TGT) or Internal Turbine Temperature (ITT)
- *Station* 5: This is the LPT exit. The main variable at this station is P50. This pressure is used to define the Engine Pressure Ratio (EPR), which is subsequently used to determine the overall engine thrust. EPR is the relation of P50 to P20.

The LP system is the combination of the fan and the LPT modules. The speed at which the LP system turns is defined as N1. The HP system is the combination of the HPC and the HPT. The speed at which the HP system turns is known as N2. In addition, the amount of fuel consumed is also monitored through fuel flow (FF).

1.2. Current techniques for aeroengine diagnosis with EHM data

High Pressure Compressor or HPC deterioration is mainly driven by increased tip clearances, which directly reduce the engine working line (Foerstemann and Staudacher, 2004). Material release from a blade or vane (Naeem, 1999) aerofoil may also be regarded as deterioration due to its effect to the working line. EHM is able to identify a blade release, or the release of a portion of aerofoil from a blade or vane, through the analysis of engine data. As a result of this assessment appropriate troubleshooting would be requested to visually determine the exact level of damage or directly propose the engine removal if the level of deterioration is known to be high. Increased tip