Cooling Fan Failure Mode Analysis to Enable Development of Automotive ECU Fan Health Monitoring System

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Abstract

Electronic Control Units (ECUs) are widely used in the automotive industry. Recent efforts to enable enhanced and automated driving requires these ECUs to process and execute computationally expensive algorithms. With these developments, the ECUs now have a higher computing power and thus are at a greater risk of overheating that can limit the availability of the essential functionalities in the vehicle. Current passive cooling may no longer be sufficient to mitigate high operating temperatures, and a cooling fan system is preferred for ECU thermal management. The fan health status monitoring is therefore critical to ensure ECU availability and reliability for vehicle operation. Traditionally, fan failures are only detected by comparing the actual fan speed against the commanded speed; however, to enable early degradation detection and prognostics, a more advanced health monitoring system is required. This paper explores fan failure mode analysis and fault injection to enable the development of prognostics. The data collection and fault injection methods were designed to capture both internal (such as motor and ball bearing) and external (such as cracking of the outer casing) failure modes. For example, the fans were exposed to multiple environmental conditions, such as dust, humidity, and heat. These conditions can potentially cause both internal and external failures. The data collection was conducted with the fans running in a standalone setup, being controlled by external equipment to ensure that the electronic input values were known. After running tests for 32 days, sufficient data was collected to enable the degradation modelling. The data will contribute to the development of a predictive algorithm which will estimate the state of health of the fan based on its performance over time. This paper will discuss the failure modes and the data collection aspects.

1. Introduction

Electronic Control Units (ECUs) play a vital role in ensuring the proper functioning of various vehicle subsystems within the automotive industry. ECUs are cooled using passive methods by physically designing the component to prevent excessive heat accumulation before it becomes detrimental to the performance. The advancements in autonomous driving have led to the emergency of highly sophisticated ECUs, necessitating more advanced thermal management solutions beyond passive cooling methods. To maintain the availability of autonomous driving features, it is imperative to employ a more efficient cooling method for these intricate ECUs, as they are prone to rapid overheating. Such a cooling method can use a small fan, similar to those used in small electronics such as computers and power supplies.

Extensive research has been conducted on small electronic fans, resulting in a comprehensive understanding of their characteristics and various failure modes (Schroeder & Gibson, 2007; Jin, Ma, Chow, & Pecht, 2012). Studies have been conducted on the failure frequencies of various small electronic components, and it has been established that the fan ranks among the top 10 components prone to failure (Schroeder & Gibson, 2007). Fan failure criteria and mechanical failures have been thoroughly studied, leading to the development of multiple methods for predicting the life expectancy of fans. These methods have been thoroughly compared to identify the most effective approach for accurately estimating fan life expectancy (Jin, Ma, Chow, & Pecht, 2012). Both external and internal failure modes have separately identified for fans, encompassing issues such as internal ball bearing failures, motor malfunctions, electronic faults, and outer casing damage caused by environmental factors. A physics-of-failure approach has been developed based on these failure modes, allowing for the estimation of fan life expectancy. Life-expectancy calculations have been employed to assess the lifespan of ball bearings and the accompanied lubricant. Furthermore, the impact of these failure modes on fan functionality has been extensively studied and quantified, prioritizing their significance (Oh, et al., 2010; Jin, Azarian, Lau, Cheng, & Pecht, 2011). The degradation of ECU fan behavior has been modelled to characterize the deterioration of ECU fan performance by correlating it with the temperature of an electronic chassis system (Hogan, 1993). Data-driven anomaly detection techniques have been utilized to detect fan failures by employing correlation analysis on fan speeds (Li, Daniel, & Ahuja, 2016).

While previous research has predominantly focused on failure modes of electronic cooling fans, there is a gap in understanding how these fans perform under the unique operating conditions of automotive applications. Although the investigated failure modes are relevant to automotive applications, it is crucial to consider that fans used in vehicles are exposed to harsher environmental conditions, which can introduce additional failure modes compared to other usage scenarios. Therefore, a comprehensive study is required to identify and address the specific failure modes that may arise in automotive environments.

This paper aims to highlight the significance of fan prognostics in automotive applications. It will identify the potential failure modes that can occur in automotive usage scenarios. Additionally, the discussion will cover fault injection methods as means to simulate and study these failure modes. Furthermore, the paper will review the data collection setup and methods employed, as the collected data will serve as a foundation for future prognostic development in this domain.

2. PROGNOSTICS ENABLEMENT

Prognostics is a valuable approach that involves predicting component failure before it happens. By employing prognostics, it becomes possible to perform preventive maintenance and mitigate the risk of significant failures. This methodology serves as a precursor to diagnostics, enabling early detection of potential issues and facilitating timely interventions. Preventive maintenance consists of scheduled maintenance or replacement of components, to ensure high functionality and avoid degraded performance. The maintenance schedule is based on the known component lifespan until it reaches degraded performance. Predictive maintenance slightly differs from this in that it is condition-based, by constantly monitoring the health of the component during operation. It evaluates the remaining component life to determine when to schedule maintenance, as opposed to using a pre-set schedule. An advantage of predictive maintenance is that the component is used until it is near failure, and there are no unnecessary or early replacements being performed. Ideally, when a useful preventive algorithm is developed, it can be expanded to perform predictive diagnosis and maintenance when the component degradation behavior is further understood.

In the automotive industry, where a wide range of vehicle components and features are present, including those related to autonomous driving, prognostics plays a crucial role in ensuring the reliability and uninterrupted operation of these systems. Moreover, since fans can be utilized to cool down ECUs in automotive applications, prognostics for fans becomes crucial in ensuring their health and functionality. By implementing prognostics for both ECUs and fans, the overall reliability and performance of these components can be upheld, thereby ensuring the continuous operation of vehicle features.

To create and validate a predictive algorithm, it is necessary to gather data throughout the lifespan of the component. This could rely on natural degradation or accelerated aging representing various failure modes. It is essential to start by collecting data for healthy components before injecting any faults. After the initial collection, the faults are injected; and data is collected to assess the impact. This is an iterative process to obtain data for multiple health stages of the component. To ensure the effectiveness of fault injection, it is crucial to conduct a comprehensive study and gain a thorough understanding of the failure modes associated with the component.

The expected fan behavior is shown in Figure 1, which will be served as a reference for evaluating the fan's performance over time. Figure 1 displays the fan speed in units of revolutions per minute (RPM), which is the core parameter to be used for determining fan health in this experiment. The RPM response to the commanded duty cycle shows agreement between the raw data and the expected RPM, although the collected data exhibits slight deviations from the expected values. It is important to note that the expected RPM values are derived from the fan datasheet provided by the manufacturer, while the raw RPM values represent the actual collected data. The slight deviation observed in the RPM

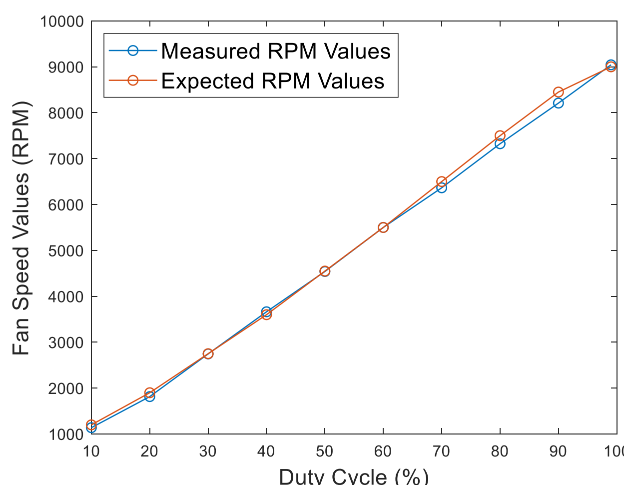

Figure 1. RPM vs. Duty Cycle curve expected values with recorded healthy fan data.

response remains within acceptable limits as defined by the fan specification, and it may be attributed to hardware variations among the fans. The data presented in Figure 1 corresponds to a healthy fan, indicating its baseline behavior. However, it is anticipated that as faults are injected, the fan's performance will deviate further from this expected behavior. The failure modes will be discussed in the next section.

3. ECU Fan Failure Analysis

ECU fan failures can be classified into two categories: external failures and internal failures. External failures primarily impact the blades and outer casing of the fan, whereas internal failures primarily affect the ball bearings, circuitry, and motor of the fan. Studying the failure modes of a small ECU fan in automotive application is crucial since these failure modes directly impact the fan's ability to effectively circulate air for thermal management. The failure mode categories are discussed in the next sub-sections.

3.1. External Failure Modes

When assessing external failure modes for an ECU fan, particular attention is dedicated to examining the condition and integrity of the fan's outer casing. The outer casing, which is usually made of plastic, plays a critical role protecting the internal components from external factors such as dust, moisture, and physical damage. Assessing the outer casing helps identify any potential issues that may affect the fan's overall performance and its ability to maintain proper thermal management within the system. The surface degrades due to dust adhesion, affecting the fan performance by impeding airflow or adding friction. The outer casing can crack, exposing the internal components to the environment. The fan blades can also crack, causing issues with airflow despite the fan meeting the commanded speed to cool the system (Oh, et al., 2010; Jin, Azarian, Lau, Cheng, & Pecht, 2011). Finally, any physical obstruction that obstructs the blades of the ECU fan, irrespective of the external environment, will hinder the airflow and can accelerate wear on the outer casing. Such obstructions can impede the fan's ability to circulate air effectively, leading to reduced cooling performance and potential overheating of the system. Additionally, the presence of blockage can cause additional strain on the fan, potentially resulting in increased wear and tear on the outer casing over time.

3.2. Internal Failure Modes

The internal failure modes for an ECU fan consider different components within the fan, including the ball bearings, motor driver, and stator. The failure modes associated with ball bearings can be attributed to various conditions. First, thermal overload can cause the internal lubricant to degrade, resulting in a bearing jam. Similar to outer surface cracking, ball cracks or spalling can be caused by cyclic loading, which causes bearing fatigue. Internal mechanical overload can cause ball bearing surface cracks as well, also known as Brinell Marks. Finally, excessive moisture can lead to corrosion, which causes wrinkles in the ball bearing (Oh, et al., 2010).

The motor driver and stator in an ECU fan exhibit distinct failure modes mainly concerned with electronic malfunctions. The motor driver has three specific failures: open circuit, short circuit, and solder connection cracking. These failures can disrupt the electrical flow within the motor driver, impacting its ability to drive the fan motor effectively. An open circuit is caused by inter-diffusion influenced by high circuit temperatures, which causes atoms to diffuse across the contact point of metals in a circuit. Short circuits are caused by dendritic growth, when ions migrate due to a voltage bias and create a bridge connecting an anode and cathode in the circuit. Solder connection failures can happen due to thermal cycling and cyclic loading, which fatigues the electronics in addition to the other components as mentioned previously. The stator has a single failure mode caused by the degradation of the insulating materials around the wires powering the component. These materials can degrade under thermal or mechanical overload and will cause a short in the wires. This will impact the function of the stator and consequently the fan (Oh, et al., 2010).

4. Fault Injection Methods

To successfully inject faults, it is crucial to conduct a comprehensive analysis of the failure modes and their underlying causes. This analysis allows for a deeper understanding of the failure modes that are specifically relevant to automotive applications. By identifying and examining these failure modes, it becomes possible to determine which faults can be realistically and feasibly injected in order to simulate real-world scenarios accurately. The targeted failure modes for this data collection are shown in Table 1.

There are three main failure modes targeted for this work: bearing failure, electronics failure, and outer casing failure. There are various causes for each of these failures as mentioned in Section 3, but the relevant ones for this experiment are summarized in the table.

To inject the faults, the relevant causes of each failure mode are introduced to the fans. Thermal conditions are introduced by operating the fans at multiple temperature levels, within a range of -30 °C to +90 °C. To introduce moisture to the fans, they are subjected to high humidity levels with a maximum of 93%, while the fans are running at varying temperatures and a constant speed. Temperature and humidity conditions are both implemented using a thermal chamber with programmable settings.

Table 1. The targeted failure modes for automotive ECU fan prognostics development.

Failure Mode	Cause	Potential Effect
Bearing Failure	Thermal overload, lubricant deterioration, moisture/corrosion build-up.	Reduced air flow, incorrect RPM response, increased vibration.
Motor or Electronics Failure	High temperature, thermal cycling, fatigue, cyclic load.	Reduced air flow, varied input current, incorrect RPM response.
Outer Casing and Blade Damage	Dust adhesion, fatigue, thermal overload, mechanical obstruction.	Reduced air flow, incorrect RPM response.

The fan data can be collected conveniently while they are housed within the chamber, allowing for data collection at any desired point during fault injection. Full duty cycle sweeps ranging from 10% to 99% are performed. These sweeps cyclically load the fan electronics at different temperatures, enabling a thorough assessment of their performance under varying thermal conditions.

To introduce dust to the outer casing, the fans are placed into a dust chamber with varying levels of oil applied to the blades. The oil allows for different amounts of dust accumulation to occur; therefore, the effect of dust adhesion can be diversely studied. Lastly, the mechanical obstruction fault can be injected in two different ways. The first method involves inserting small pieces of wood in-between the fan blades, serving as a relatively large obstruction that hampers airflow. This obstruction simulates a scenario where a relatively large object impedes the movement of the blades. In the second method, small wires are positioned in close proximity to the fan blades. This approach introduces friction on the blades without creating a substantial blockage. By doing so, it emulates a situation where there is a minor interference or resistance in the fan's rotation, which can affect its performance and efficiency. These two approaches allow for the simulation of different mechanical obstruction scenarios, enabling the assessment of the fan's response and behavior under varying levels of obstruction and friction. The actual experimental setup is discussed next.

5. Experimental Setup

The experimental setup, shown in Figure 2, contains both an Arduino and National Instruments Data Acquisition Device (NI DAQ) for data collection. Both components are accompanied by a LabView code to control the fan input duty cycle and the temperature of the chamber. The NI DAQ is connected to LabView to record the output frequency of the fans, the commanded duty cycle, and the temperature of the chamber. The LabView code records these readings as individual files for each test. The Arduino is connected to a sensor (i.e. INA219) to monitor the current, voltage, and power being supplied to the fans. An additional application, PuTTY, has been used to record the power related data measured using Arduino due to difficulties with recording the data using NI DAQ. PuTTY is an open-source terminal emulator and serial console, and thus can be used to record the values printed to the Arduino serial monitor (Tatham, 2022).

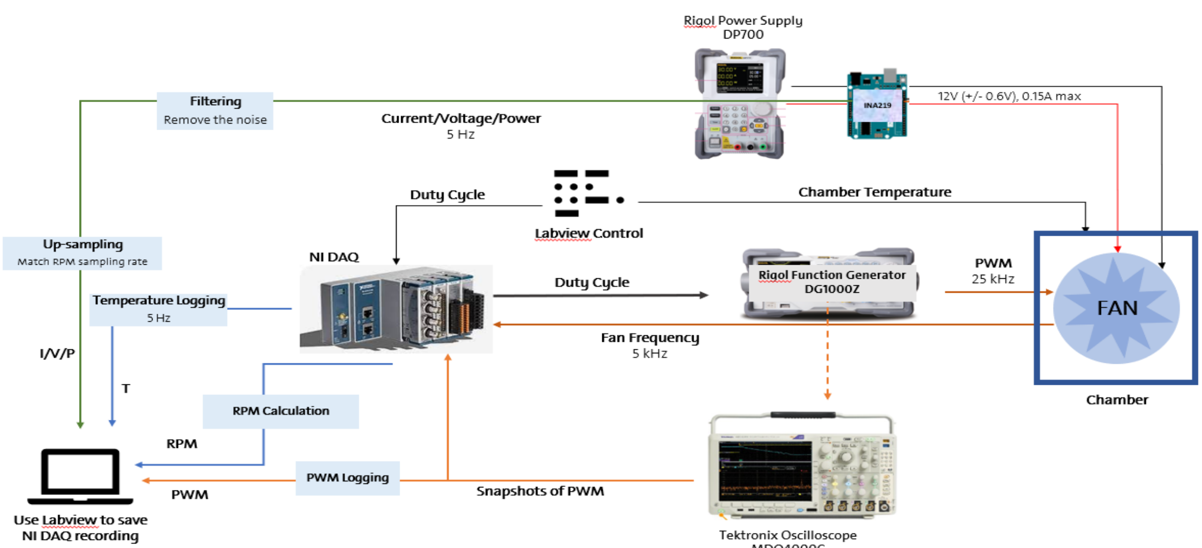

Figure 2. Block diagram of experimental setup with additional information about each component

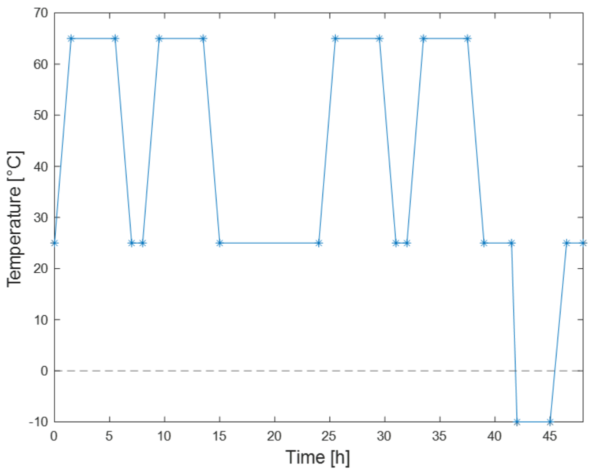

Figure 3. Cyclic humidity profile used for fault injection. The temperature variation is shown here, and the humidity is maintained at a level of 93% for the majority of the test. Humidity drops to 80% during temperature transitions, and is uncontrolled at temperatures below 0 °C.

In addition to the setup to record the data, the fans were placed inside chamber to simulate various operating conditions including temperature and moisture. The temperature and humidity conditions were both applied to the fans for multiple days, to test the fans robustness while running in a high-stress environment. The cyclic temperature and humidity profile used during fault injection is shown in Figure 3. This profile is 48 hours long and was continuously repeated for the duration of the fault injection.

The shortest period that the fans were in the chamber was 8 days, while the longest was 32 days. The fans were placed in the chamber throughout the entire fault injection period, with optional data collection as the faults were injected. The dust exposure was applied for a 16-hour period before entering the humidity chamber. These periods were chosen for fault injection due to their extremity compared to the fan validation testing. Subjecting the fans to extreme testing would encourage degradation within a short time, which will enable prognostic development.

The recording data lasted for a period of 32 days. Figure 4 illustrates the overall timeline that was adhered to during the testing and fault injection process. It is worth mentioning that, within the fault injection periods, the fans were subjected to five temperature sweeps, as indicated by the red stars in Figure 4. These temperature sweeps were intentionally conducted to simulate specific faults. The data collected during this time encompasses different stages of component health, providing a comprehensive representation of their varied conditions. A total of twelve fans were used for the testing phase, with each fan subjected to various combinations of fault injections. This deliberate approach ensured the creation of a diverse dataset, encompassing different known control factors. The structure of the data and the methodology employed for its collection are thoroughly examined in Section 6. Finally, the fans included in the setup are driven by brushless direct current motors. The electronic circuitry implemented has capability to power run and collect data for a maximum of six fans simultaneously. To enhance efficiency during specific tests, data was collected concurrently from all six fans. To facilitate fault injection accurately track the data collected for each fan, appropriate labelling was employed throughout the testing process.

6. Data Collection

Data was collected across a range of operating conditions to assess the effects of different conditions on the fan performance. Two LabView scripts were employed to control the fans. The first script allowed for the fans to be commanded to operate at a duty cycle determined by the user, with the ability to set a specific duration for this operation. This was utilized for monitoring the fans while they are enclosed within the dust chamber or the thermal chamber during fault injection. This script allows for real-time observation and data recording of the fan's behavior and performance under specific fault conditions. The second LabView script, on the other hand, controlled both the temperature chamber and the duty cycle input. It facilitated a systematic sweep across a range of temperature and duty cycle values. This script was employed to collect thermal sweep data at different health stages following the injection of each fault. The temperature sweep spanned from -30°C to 90°C, while the duty cycle sweep ranged from 10% to 99%. An example of the output data from this script is shown in Figure 5. The data includes RPM values and corresponding chamber temperature readings. It can be observed in Figure 5 that at certain temperatures, the duty cycle sweep was performed twice unintentionally. However, this does not have a negative impact on data analysis. Both LabView scripts work in conjunction with the Arduino PuTTY data collection system, enabling the simultaneous recording of corresponding circuit data.

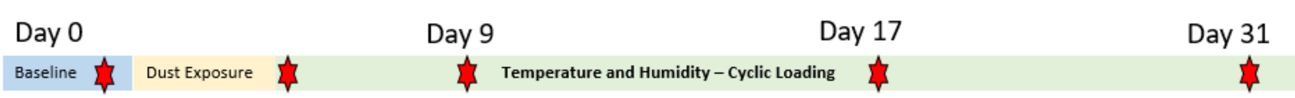

Figure 4. Fault injection timeline with various fan faults. The red star represents all instances when temperature sweep data was collected, to observe fan behavior at different degradation levels.

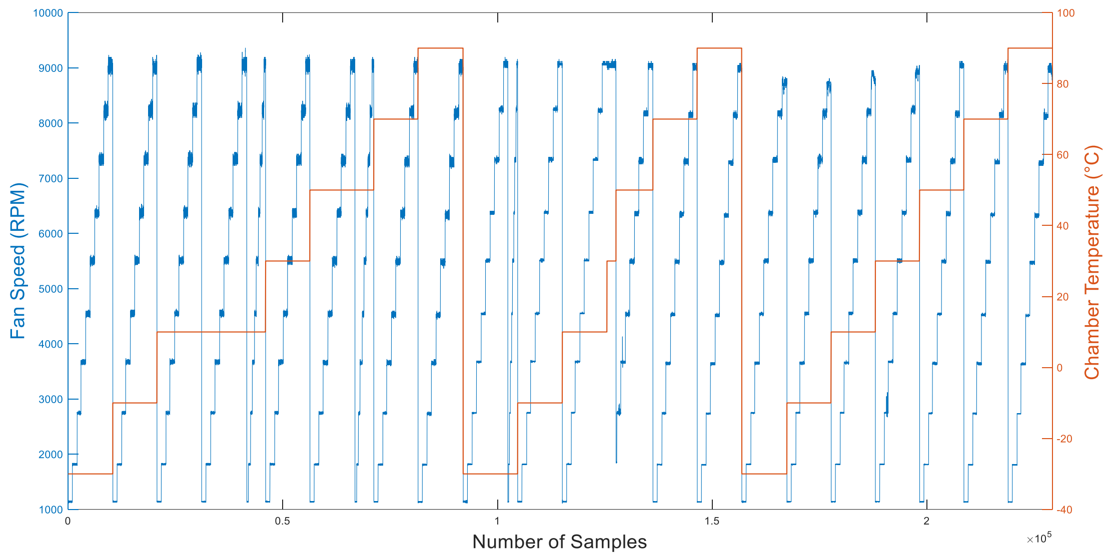

Figure 5. The raw temperature and RPM data collected over multiple days.

The LabView scripts generate two files that are utilized for analysis purposes. The first file contains fan output frequency, while the second contains the commanded duty cycle and temperature. The former is recorded at a rate of 5 kHz, while the latter is recorded at 5 Hz to avoid large file sizes. Additionally, one file is produced using PuTTY which contains current, voltage, and power of the circuit at a rate of 5 Hz. During the data collection process an additional file is generated that captures a snapshot of the duty cycle input at each duty cycle change. This is accomplished by connecting the function generator to the oscilloscope, which displays and records the duty cycle values. When a snapshot is saved, the corresponding flag time is recorded in the PuTTY file. This flag time serves as a reference point to facilitate data synchronization, ensuring that the duty cycle data aligns accurately with other recorded measurements.

To utilize the data for prognostics development effectively, it is essential to synchronize the data files and simulate time-series data. To sync the data, the fan frequency was used to calculate the RPM, using a moving window of 250 ms with a 0.05 ms step size, resulting in a data frequency of 20 Hz. The remaining two data files were then up-sampled to match the frequency of the calculated RPM. The resultant data is comprised of all signals collected by LabView and PuTTY, the labeled fan number, and the known degradation level. For this data, the degradation level refers to the number of days for which the faults have been injected.

7. Preliminary Results and Discussions

By studying the fan RPM over time, the effects of fault injection on the fans can be observed. Analysis revealed that the chamber temperature has a significant impact on fan performance at a specific duty cycle, as demonstrated in Figure 6. It is evident that higher temperatures result in more noticeable differences between degradation levels. The measured RPM gradually deteriorates over time, failing to achieve the same level of performance as when the fan was in a degraded health state, as depicted in both Figure 6 and Figure 7.

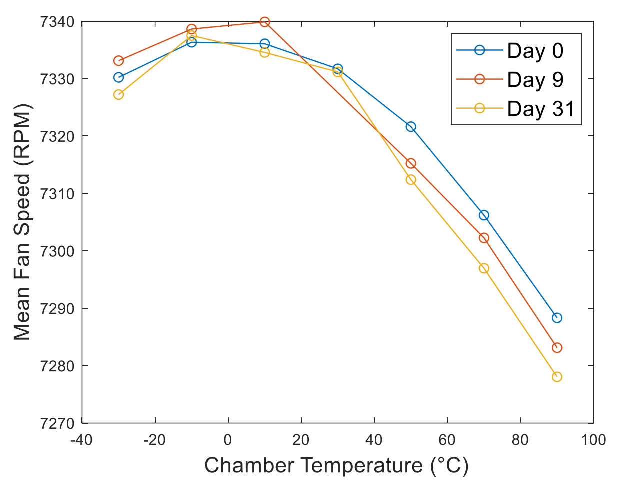

Figure 6. Plot of the mean RPM vs. Temperature at a specific duty cycle, for multiple degradation levels.

In Figure 7, a boxplot representing the mean RPM further illustrates the degradation in performance at a specific high temperature, such as 70 °C. The 32-day duration of the data collection period proves sufficient for observing and modeling early-stage degradation. Consequently, this enables the development of health indicators and prognostic techniques. To model the complete operational lifespan of the component, additional data can be collected to encompass later stages of degradation. By analyzing the observed trends in fan RPM, valuable insights can be gained regarding the effects of fault injection on performance degradation over time. These findings lay the foundation for the development of prognostic models and health indicators to predict and monitor the fan's condition throughout its operational lifespan.

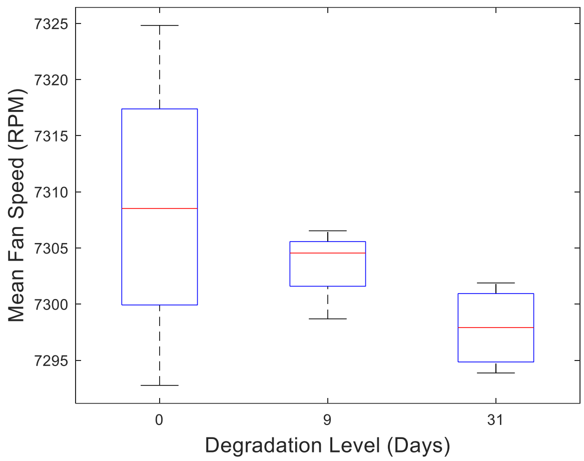

Figure 7. Boxplot of mean RPM at a specific temperature, to show the trend as the fans become degraded.

8. CONCLUSION

After conducting a comprehensive study on ECU fan failure modes, relevant ones for automotive applications were identified. Subsequently, fault injection methods were developed and applied to twelve fans, with data collected for each test case. Upon processing the collected data, preliminary observations indicate that the fault injection has a lasting impact on fan performance, particularly affecting the RPM response. Furthermore, it is evident that the RPM response is sensitive to variations in external temperature.

Those observations, coupled with the collected data, serve as a valuable foundation for the development of a prognostic algorithm aimed at monitoring the health status of ECU fans. By analyzing key parameters such as fan output frequency, commanded duty cycle, and temperature data, it becomes feasible to identify patterns, trends, and potential indicators of fan degradation. If the degradation behavior can be accurately modelled, it also becomes feasible to quantify the amount of RPM degradation at which a failure would occur. Such analysis enables the estimation of the remaining operational time for ECU fans in automotive applications.

By leveraging the insights gained from the observation and analysis of fan performance data, a prognostics algorithm can be devised to provide proactive monitoring and assessment of ECU fan health. The algorithm would contribute to ensuring reliable and efficient operation of ECU fans in automotive systems, enhancing overall system performance and longevity. Moving forward, the focus will be on developing a prognostics algorithm that can effectively utilize the collected data. This algorithm aims to translate the insights gained from the data into a practical application, enabling its real-world implementation. By leveraging the collected data and applying advanced analytical techniques, the prognostics algorithm will be designed to provide actionable information and predictions regarding the health status and remaining operational life of the ECU fans.

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BIOGRAPHIES

Jacqueline Del Gatto received an engineering physics degree with a sub-focus in mechanical engineering from Queen's University, Canada, in 2022. Before graduation, she worked at General Motors for a brief period as a data analytics engineer, working on SuperCruise performance analytics and root-causing. She then moved to the prognostics space to work on CAN network health monitoring and LiDAR sensor performance. After graduation, she returned to General Motors for a permanent position as a prognostic engineer, and is currently working on health monitoring for multiple vehicle components, including ECU fans.

Alaeddin Bani Milhim received the B.A.Sc. degree in mechanical engineering from the Jordan University of Science and Technology, Jordan in 2008; the M.A.Sc. degree in mechanical engineering from Concordia University, Quebec, Canada in 2010; and the Ph.D. degree in mechanical engineering from the University of Toronto, Canada in 2016. He has been working at General Motors of Canada in the Canadian Technical Centre since 2016; and currently holds the technology insertion lead position in Advanced Vehicle Prognostics team under ADAS and Autonomous organization. His research interests include mechatronics, vehicle health management, smart sensors and actuators, and piezoelectric thin film. He received the Boss Kettering Award from General Motors for his contribution in Lane Change on Demand development in 2021.

Hossein Sadjadi received his Ph.D. degree in electrical engineering from Queen's University, Canada, and M.Sc. degree in mechatronics and B.Sc. degree in electrical engineering from the American University of Sharjah, UAE. He has been working at General Motors, Canadian Technical Center since 2017, and is currently the Global Technical Specialist for Vehicle Health Management. He had also served as a post-doctoral medical robotic researcher at Queen's university, senior automation engineer for industrial Siemens SCADA/DCS solutions, and senior mechatronics specialist at AUS mechatronics center. His research interests include prognostics, autonomous systems, and medical robotics. He has published numerous patents and articles in these areas, featured at IEEE transactions journals, and received several awards.