FAULT DETECTION FOR AN AIRCRAFT ELEVATOR

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Abstract

In aviation safety and performance play a pivotal role, and a critical theory part is fault detection, which can be used in subsystems that are important in ensuring the reliability of aircraft systems. This research delves into the implementation and testing of an architecture for fault detection using parity space methodology, specifically tailored to handle different maneuvers during the flight of an aircraft. The emphasis on maneuver-specific techniques aims to enhance fault detection's overall robustness and accuracy in dynamic flight conditions. This work is intended to study two different forms of implementation for detecting faults in the actuator system of an aircraft, they will be tested using two actuator models for the elevator in a simple maneuver during the flight.

Keywords: Parity Space, Fault Detection, Safety, Performance.

1. Introduction

Safety is one of the cornerstones of the aviation industry, essential not only for passenger reassurance but also for the viability of air travel on a global scale. With millions of passengers relying on air transportation daily, ensuring their safety is paramount. Each flight involves the interplay among myriad systems, operating in harmony, from the aircraft's mechanics to the sophisticated control systems guiding its trajectory. Any failure within these systems can have catastrophic consequences, underscoring the critical need for robust safety measures. Moreover, safety isn't merely a concern for passengers; it's a moral imperative for airlines, regulatory bodies, and manufacturers. The public's trust in aviation hinges on the industry's unwavering commitment to safety, making it a non-negotiable priority[1], [2].

Moreover, as technological advancements and increasing complexity in aircraft design, the pursuit of safety has evolved beyond conventional methodologies. The aeronautical industry grapples with the challenge of preempting and mitigating potential hazards before they escalate into crises. This proactive approach requires the integration of advanced control theory for failure detection and isolation, enabling real-time monitoring and swift responses to anomalies[3]. By leveraging technologies such as predictive analytics, aviation stakeholders can enhance safety protocols, identifying potential issues before they compromise flight operations. Consequently, investing in the research and development of such systems is not just an option but a necessity.

As shown the aviation industry continuously seeks advancements in safety and reliability, given the focus on aircraft control systems, the reason for this is the possibility of implementation of software features capable of checking the actuator's health and conditions, allowing future upgrades much easier than changes in the aircraft physical systems.

So for verifying the actuator failures, one needs to be aware that this can have different sources stemming from various factors such as wear, malfunction, or external disturbances, which pose a critical challenge to the operational integrity of aircraft[4]. This paper explores the task of fault detection and tries to generate fault isolation capability within subsystems of an aircraft. The proposed methods address the challenges of identifying and isolating faults during flight maneuvers commanded by the elevator.

The method implemented in this work is the parity method which is an approach for detecting and isolating failures within complex systems such as in the aeronautics industry. This method hinges on comparing the actual system behavior against expected or nominal behavior, extracting weighted residuals that encapsulate deviations indicative of faults or anomalies [5], [6].
Analyzing these residuals, engineers can pinpoint the root cause of malfunctions and promptly initiate corrective measures, thereby minimizing downtime and enhancing operational reliability [7]. The parity method offers a systematic framework for detecting and isolating faults across various subsystems, facilitating proactive maintenance strategies and optimizing overall system performance.
One of the key advantages of the parity method lies in its versatility and adaptability to diverse applications and system architectures. By applied to aircraft propulsion systems, chemical plants, or power generation facilities, this method provides a unified framework for fault diagnosis and mitigation.
As industries increasingly prioritize reliability and operational efficiency, the parity method emerges as a vital tool in the arsenal of fault management strategies, offering a proactive approach to safeguarding critical infrastructure and maximizing uptime[8].
The last part of this introduction is intended to show an operational view of the research. The project implementation is based on the diagram from the Fig. 1.

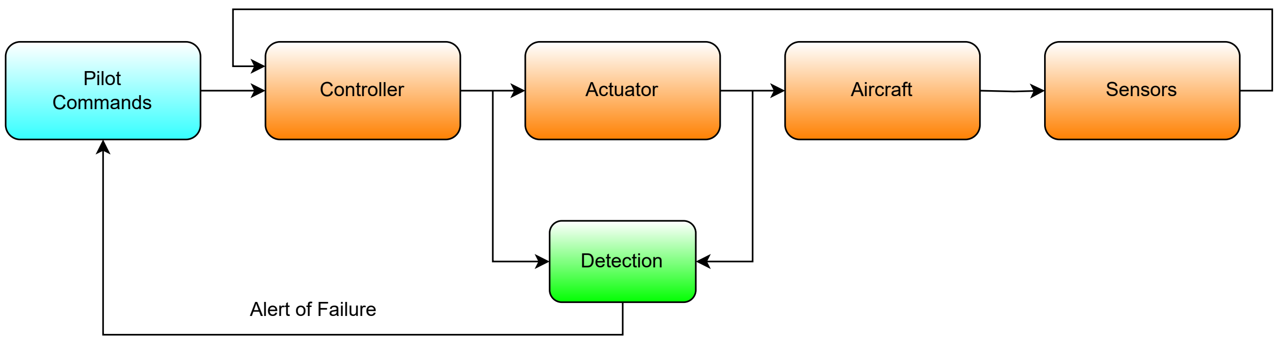

Figure 1 – Project Diagram.

So in the first place, the pilot gives the controller of the aircraft the necessary inputs to perform a desired maneuver, when the controller receives it, determines the deflections of the control surfaces needed to complete the maneuver and then calculates the correct control action for each actuator needed, the actuators receive this controls actions inputs, produce the desire deflections and the aircraft dynamics responses to it, in the end the sensors of the aircraft gives the controller the measures of the performance.
This diagram is a simplification of the flight control laws that are used in the aeronautics industry. This work implements the new block of detection, which is intended to monitor the health of the actuator in real-time using the parity space methodology.
The next section is a more complete explanation of the actuator modeling and parity space method.

2. Background

This part of the work is a detailed presentation of the considerations done modeling the dynamics of the actuators and implementation of the detection algorithm.

2.1 Actuator modeling

Here are some notes and understanding about the importance and study of the actuator dynamics and how the process responds to those dynamics.
Considering that the actuators in an aircraft fly-by-wire are normally electrohydraulic ones, one can use the theory of differential equations to obtain the models in the format of transfer functions, another important and useful assumption is that the dynamic of the electrical and electronic parts of the system can be removed from the model, then one can only consider the hydraulic part of the mechanism.
Using the methodologies in [9] and [10], [11], one can develop the following model for the elevator of an aircraft.

$$G(s) = \frac{\alpha}{s+\alpha}, \tag{1}$$

where $\alpha = \frac{1}{\tau_{elevator}}$, and $\tau_{elevator} = \frac{1}{30}$.
Now one can analyze this first-order transfer function knowing that the response always goes to the value applied in the input in a finite time, but going there will take four times the time constant $\tau_{elevator}$. This behavior is shown in Fig. 2.

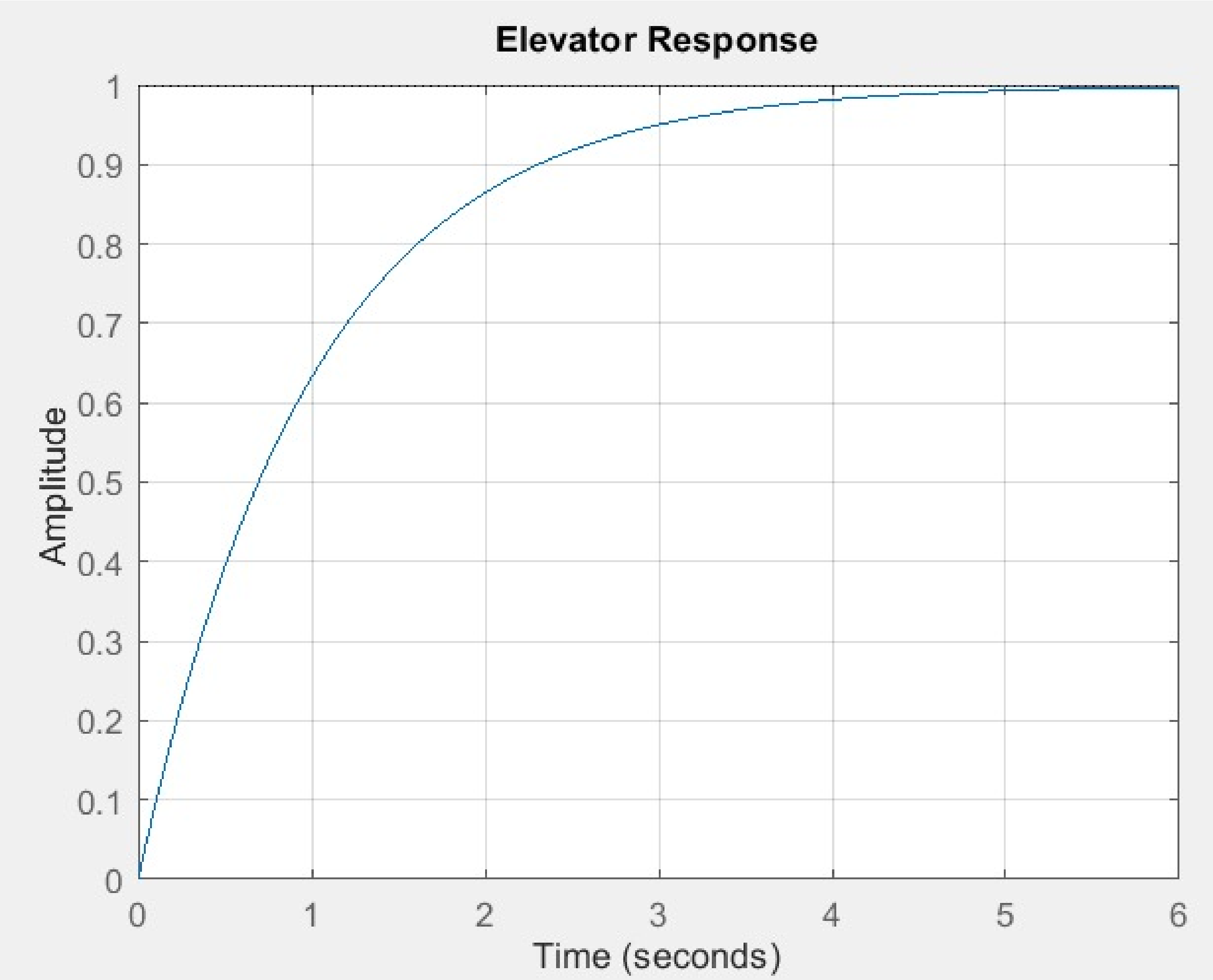

Figure 2 – Elevator time response

The next subsection explains the parity space methodology and its implementation.

2.2 Fault detection algorithm

Now it's given a more detailed presentation on the parity space technique for fault detection, here the implementation is based on the works of [5], [7], [12], and [13].
The Fig. 3, shows a methodology for implementing the parity space technique.
So as shown before, first of all, obtain the system's discrete state space representation as in Eq. 2.

$$\begin{aligned} \dot{x}[k] &= \mathbf{A}x[k] + \mathbf{B}u[k] \\ y[k] &= \mathbf{C}x[k], \end{aligned} \tag{2}$$

in this implementation, the system is considered proper and without disturbances. So now must be chosen the size of the window for prediction, one can see in Eq. 3 the problem of selecting a large window.

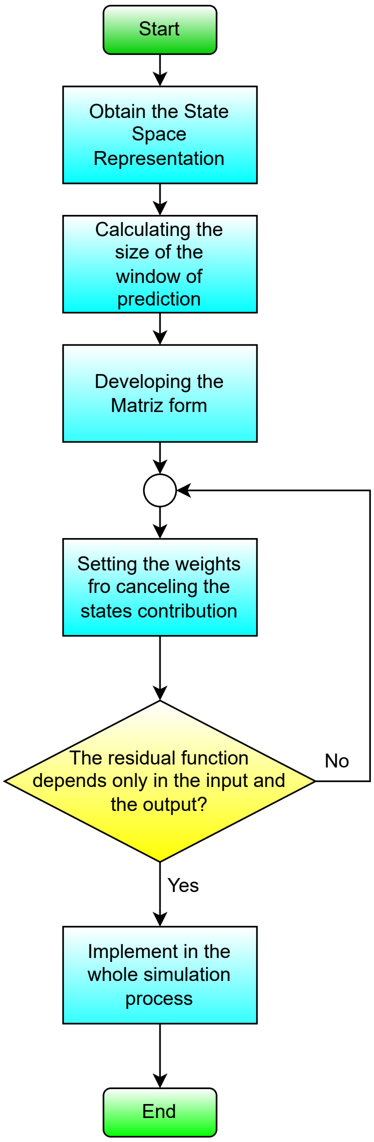

Figure 3 – Parity Space Implementation Algorithm.

$$\begin{bmatrix} y[k] \\ y[k+1] \\ y[k+2] \\ \vdots \\ y[k+q] \end{bmatrix} = \begin{bmatrix} \mathbf{C} \\ \mathbf{CA} \\ \mathbf{CA}^2 \\ \vdots \\ \mathbf{CA}^q \end{bmatrix} \mathbf{x}[k] + \begin{bmatrix} 0 & 0 & 0 & 0 & 0 \\ \mathbf{CB} & 0 & 0 & 0 & 0 \\ \mathbf{CAB} & \mathbf{CB} & 0 & 0 & 0 \\ \mathbf{CA}^2\mathbf{B} & \mathbf{CAB} & \mathbf{CB} & 0 & 0 \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ \mathbf{CA}^{q-1}\mathbf{B} & \mathbf{CA}^{q-2}\mathbf{B} & \dots & \mathbf{CB} & 0 \end{bmatrix} \begin{bmatrix} \mathbf{u}[k] \\ \mathbf{u}[k+1] \\ \mathbf{u}[k+2] \\ \vdots \\ \mathbf{u}[k+q] \end{bmatrix} \tag{3}$$

The Eq. 3 can be organized in the compact form as in Eq. 4[1].

$$\mathbf{Y}[k] = \mathbf{Q}_x\mathbf{x}[k] + \mathbf{Q}_u\mathbf{U}[k] \tag{4}$$

Now the Eq. 4 needs to be changed to Eq. 5.

$$\mathbf{w}^T\mathbf{Y}[k] = \mathbf{w}^T\mathbf{Q}_x\mathbf{x}[k] + \mathbf{w}^T\mathbf{Q}_u\mathbf{U}[k] \tag{5}$$

Where weight vector $\mathbf{w}$, must satisfy the constraints in Eq. 6.

[1] It's important to note here that this formulation can handle MIMO systems.

$$\begin{aligned} \mathbf{w}^T \mathbf{Q}_x \mathbf{x}[k] &= 0 \\ \mathbf{w}^T \mathbf{Q}_u \mathbf{U}[k] &\neq 0 \end{aligned} \tag{6}$$

When this is met one has the Eq. 7, which implements a residual generator of the expected behavior against the real/observed of the system.

$$r[k] = \mathbf{w}^T \mathbf{Y}[k] - \mathbf{w}^T \mathbf{Q}_u \mathbf{U}[k] \tag{7}$$

The fault detection method is calculated and must be integrated into the rest of the simulation.
The case where the actuator doesn't show failure or loss of performance is presented as a baseline response for the research, i.

3. Baseline: Study without failure

In Fig. 4 one can see how the study starts, a study on how the dynamics of the aircraft evolve on time without failure applying a step to its elevator. In other words the simulation of the nominal system.

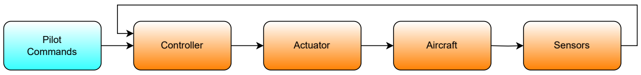

Figure 4 – Base line study.

And important note is that the model used for this research is from [14].
Following Fig. 5 shows the change in the altitude after a command in the elevator. Because the failure study is conducted in the dynamics of the actuators mounted in the aircraft, an important feature is the altitude response, which can be seen in Fig. 5.

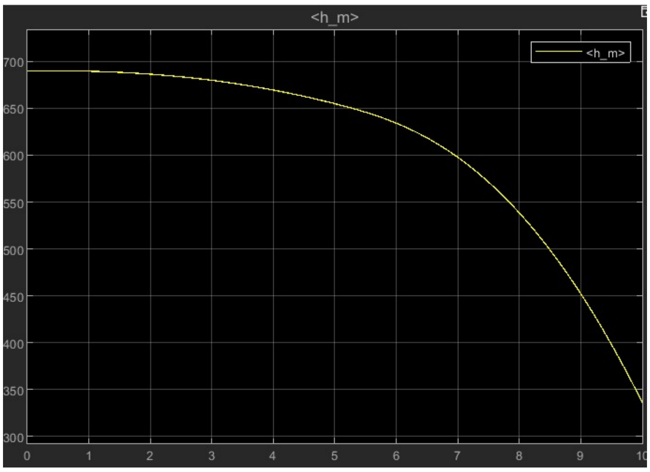

Figure 5 – Altitude response without failure.

After looking at Fig. 5 need to look at the response of the actuator, which is shown below in Fig. 6, part of the analysis is from [15], and [16].
In the end, one can see that using the nominal actuator and the normal operation mode, there aren't problems with the response.

4. Case 1: Failure active and first method of detection

The failure scenario simulated on the elevator involves its incapacity to reach the prescribed operational limits—a critical malfunction that demands rapid detection and response. The overarching objective is twofold: firstly, to swiftly identify this anomaly within a constrained timeframe, and secondly, to initiate preemptive measures through the aircraft's control system.
This approach facilitates timely communication with ground control. In the event of a detected failure, it is imperative to provide the pilot with ample opportunity to issue a distress signal, thereby enabling

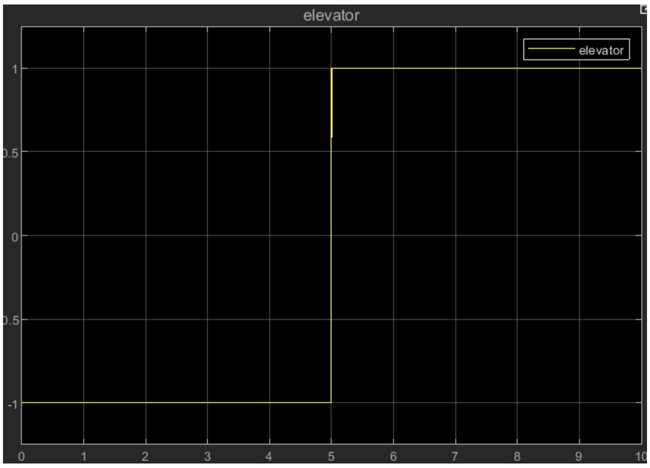

Figure 6 – Elevator response

ground personnel to prepare for potential emergency scenarios. The conceptual framework for addressing this situation is delineated in Figure **??**, outlining the proactive steps taken to identify and mitigate elevator failures.
Following the simulation, the altitude response, as depicted in Figure 7, provides valuable insights into the ramifications of the elevator failure. This visual representation underscores the significance of detecting such anomalies promptly, as it allows for a more informed decision-making process regarding subsequent corrective actions. Overall, the proactive detection and mitigation of elevator failures are paramount in ensuring the safety and operational efficiency of aircraft systems.

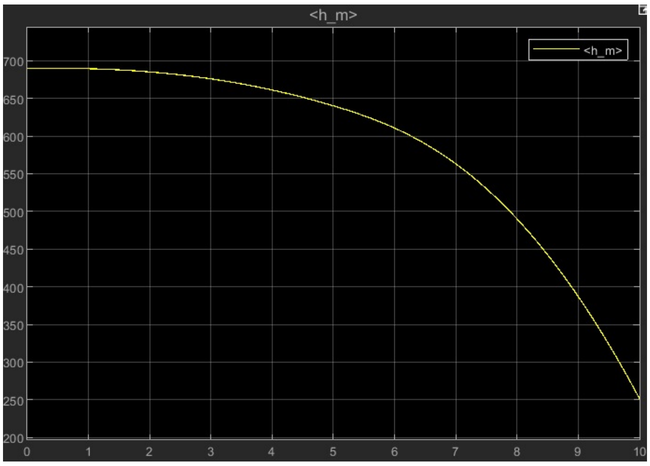

Figure 7 – Altitude response in failure.

The input signal received by the elevator control system is illustrated in Figure 8. This visual representation offers a clear depiction of the data stream directing the aircraft controller, providing valuable insights into the operational dynamics of the system. Analyzing this input signal is instrumental in understanding the behavior of the elevator, particularly in the context of fault detection and response strategies.
It's important to note that the simulated movement depicted in Figure 8 represents the elevator reaching its full extension, thereby showcasing the operational limits of the system. This simulation provides a crucial reference point for evaluating the performance of the elevator control system and detecting deviations from expected behavior. By simulating the full extension of operational limits, engineers can assess the system's responsiveness and resilience under various conditions, ultimately contributing to the enhancement of overall system reliability and safety.
The response of the parity space method to deviations in system behavior over time is depicted in Figure 9. This visualization provides valuable insights into how the parity space technique dynamically adjusts to anomalies in the system, offering a real-time indication of its efficacy in fault detection

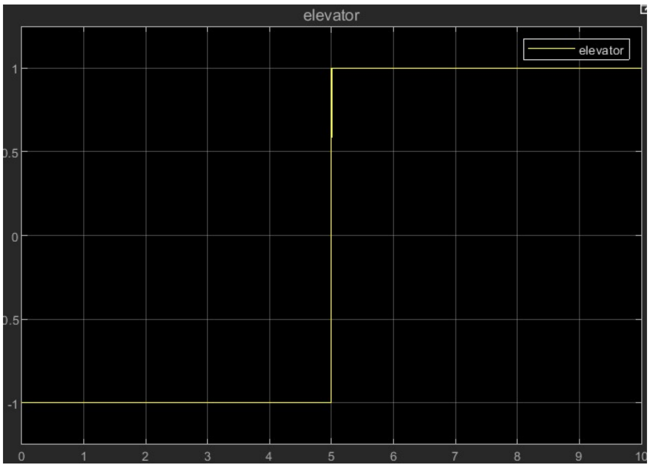

Figure 8 – Elevator with failure.

and diagnosis.

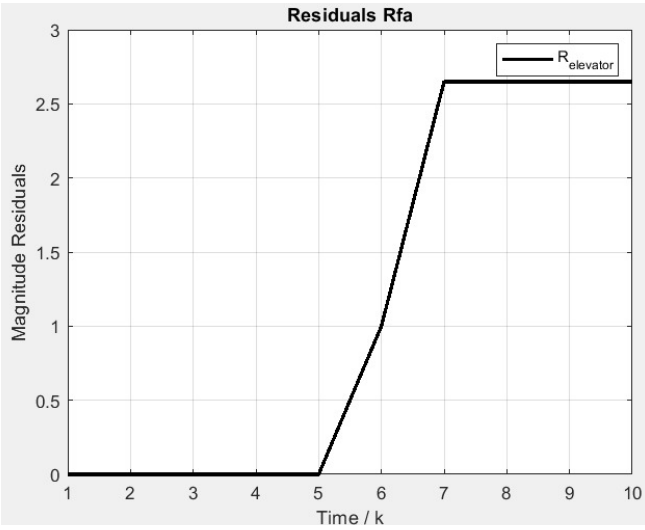

Figure 9 – Residual evolution in time.

As time progresses, the accumulated error within the system gradually influences the output of the residual generator. Eventually, this accumulation reaches a critical threshold, prompting the residual generator to issue an alarm signal. This signal serves as an early warning mechanism, alerting operators to the presence of a fault within the system and enabling timely intervention to mitigate potential consequences.

The transition from normal operation to alarm status highlights the sensitivity and responsiveness of the parity space method in detecting deviations from expected behavior. By monitoring the evolving response of the system through the parity space approach, engineers can proactively identify and address faults before they escalate into critical failures, thereby enhancing overall system reliability and safety.

5. Conclusions

In this initial phase of our research, it becomes evident that under ideal conditions, a straightforward calculation can yield insightful results. This milestone serves as a foundational step, showcasing the potential of our approach and setting the stage for further investigation and refinement.

In summary, our utilization of parity space for fault detection in the aircraft elevator model has delivered promising outcomes, cementing its status as a dependable diagnostic technique. Through rigorous analysis and experimentation, our study showcases the algorithm's proficiency in accurately pinpointing faults within the elevator system. By harnessing the redundancy inherent in the parity space methodology, we have effectively identified and isolated faults, thereby upholding the safety and operational integrity of aircraft.

Furthermore, the successful deployment of our fault detection algorithm highlights its applicability in real-world scenarios within the aviation sector. The algorithm's resilience and precision offer a tangible avenue for enhancing aircraft safety measures and maintenance protocols. As the aviation landscape evolves, the integration of innovative fault detection methodologies like parity space analysis presents an avenue for optimizing aircraft performance and reliability.

Ultimately, our research emphasizes the pivotal role of proactive fault detection methodologies in safeguarding the dependability and security of intricate systems such as aircraft elevators. The demonstrated effectiveness of the parity space technique not only validates its utility but also lays the groundwork for future advancements in fault detection and diagnostics across diverse industries. Moving forward, continuous exploration and refinement of such methodologies will be instrumental in advancing safety standards and operational efficiency, both in aviation and beyond.

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7. Copyright Statement

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