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Design and Exploration of a Virtual Simulation Experiment Project for Typical Fault Analysis in Aviation Engines

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Abstract: Aviation engines are classic examples of complex thermodynamic systems. They operate under conditions of high temperature, high pressure, and high rotational speed. As a result, real-world fault testing is characterized by high cost, high risk, limited data accessibility, restricted operation, and poor reproducibility. To address these problems, this paper presents a systematic and hierarchical design for a Virtual Simulation Experiment Project on Typical Aviation Engine Fault Analysis. Starting from the basic operating principles of turbojet and turbofan engines, the project systematically discusses several typical failure modes, including compressor stall and surge, fuel supply anomalies, lubrication system malfunctions, rotor imbalance, blade damage, foreign object ingestion, and sensor drift. A virtual experiment framework is established based on the teaching sequence of structural analysis → parameter monitoring → fault injection → mechanism investigation → diagnostic decision-making → report evaluation. On this basis, the paper proposes an experimental approach that integrates 3D visualization, thermodynamic cycle models, fault rule libraries, parameter trend simulation, and closed-loop learning evaluation. Traditional aviation engine testing has obvious limitations in visualizing internal processes and simulating hazardous or complex operating conditions. Therefore, this virtual simulation project transforms engine fault mechanisms, maintenance procedures, testing methods, and health management concepts into interactive experimental tasks. By integrating engine theory, control systems, and testing technology, the project provides a safe, cost-effective, repeatable, and evaluable platform for aviation engine fault analysis teaching.

Keywords: Aero-engine; Typical faults; Virtual simulation; Fault diagnosis; Air path analysis; Experimental teaching

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1. Introduction

Since aircraft engines are vital to flight safety, they are often referred to by aero-engineers as the "heart" of an aircraft. Due to their importance in mission reliability and maintenance cost control, classroom instruction alone is insufficient for aerospace engineering students.

To properly understand engine structure, airflow parameters, and fault indicators, students need to combine real-world engineering principles with virtual simulation methods. Therefore, using simulation technology to design typical fault analysis experiments that are observable, operable, repeatable, and evaluable has clear teaching value and engineering significance. From the perspective of teaching reform, this approach is both necessary and practical.

Virtual simulation experiments should not be regarded as a simple substitute for physical experiments. Instead, they should serve as an effective complement to experimental procedures that are high-risk, costly, irreversible, and difficult to replicate. By combining physical models, data-driven methods, and expert knowledge, the proposed approach can support accurate fault diagnosis, good generalization ability, and strong engineering applicability under complex operating conditions [1].

Virtual simulation experiments should not merely present results. Although animations can be used, the core purpose is to enable students to analyze real parameters, understand real mechanisms, and develop authentic diagnostic reasoning. This paper, entitled "Design and Exploration of a Virtual Simulation Experiment Project for Typical Fault Analysis in Aero-Engines," mainly addresses three questions. First, what traditional teaching problems can be solved through virtual simulation? Second, how can engine structure, thermodynamic cycles, parameter monitoring, and fault diagnosis be integrated into a feasible experimental project? Third, how can an experimental evaluation mechanism be established to promote students' engineering competencies?

From the perspective of student development, the project guides students from phenomenon observation to evidence identification, mechanism clarification, and solution proposal. The curves and matrices presented in the project are used as instructional modeling examples to illustrate the project design methodology. However, it should be clearly stated that they are not intended to replace actual engine test data or official maintenance manuals.

2. Theoretical basis for typical failure analysis of aviation engines

The fundamental operating process of turbojet and turbofan engines can be summarized as intake, compression, combustion, expansion for work generation, and exhaust acceleration. The basic mechanism by which a propulsion system generates thrust is the acceleration of the working fluid. Therefore, thrust is directly related to both the mass flow rate through the engine and the gas outlet velocity [2].

Gas turbine engines use compressors to increase air pressure. The engine operates through a well-defined process: the combustion chamber mixes fuel with compressed air and burns the mixture; the turbine extracts power from the high-temperature gas to drive the compressor; and the nozzle converts the remaining energy into a high-speed jet [3]. Therefore, an important characteristic of engine failures is that any component fault will eventually be reflected in operating parameters such as rotational speed, temperature, pressure, fuel flow rate, and vibration.

Fault diagnosis is an essential part of engine health management. It can generally be divided into four levels: detection, isolation, identification, and prediction. Detection determines whether an anomaly exists; isolation identifies which system or component is affected; identification determines the type and severity of the fault; and prediction estimates performance degradation trends or remaining service life [4].

The NASA C-MAPSS turbofan engine degradation simulation dataset provides a useful reference for describing the evolution of an engine from normal operation to failure as a multivariate time series. Since different operating conditions and fault modes are included in such datasets [5], they can support the design of educational experimental tasks involving time-series analysis, parameter trend analysis, and condition comparison. These tasks are important for helping students master the basic methods of typical fault analysis [6].

The goal of typical fault analysis is not simply to memorize fault names, but to establish a clear mapping relationship among mechanisms, parameters, and mitigation measures. For example, compressor stall is usually caused by partial or complete airflow separation within the compressor, leading to abnormal changes in flow rate and pressure ratio. In severe cases, compressor surge may occur. Characteristic parameter changes may include abnormal noise, rotational speed fluctuations, high exhaust gas temperature, and reduced thrust.

Fuel supply abnormalities are usually related to faults in the fuel pump, fuel metering system, nozzle, or control logic, which cause the fuel flow rate to deviate from the required level. These faults may appear as difficult starting, acceleration lag, lean-fuel-induced flameout, or rich-fuel-induced overheating [7].

Lubrication system failures can adversely affect bearings and rotor systems. Insufficient lubrication or cooling usually manifests as combined abnormalities in oil pressure, oil temperature, and vibration parameters. Since virtual simulation experiments focus on fault mechanisms, these mechanisms should be transformed into observable, comparable, and reproducible parameter variations [8].

3. Typical fault objects and teaching modeling

Table 1. Design a table of typical failures, mechanisms, and symptoms of aviation engines

Fault type	Dominant mechanism	Typical signs	Key areas of teaching and training
Compressor stall/ buzzing	Air flow separation, mismatch between pressure ratio and rotational speed, intake distortion, or rapid fuel injection	EGT spikes, N1/N2 waves, P3 abnormalities, decreased thrust	Surge margin, exhaust valve, thrust reduction mechanism
Abnormal fuel supply	Abnormalities in the fuel pump, filter, metering valve, nozzle, or control signal	Limited or excessive fuel flow, difficult starting, delayed acceleration, overheating, or engine stall	Fuel – Revolution Rate – Temperature Coupling
Abnormality in the lubricating oil system	Insufficient lubrication/cooling, oil filter clogging, bearing wear	Low oil pressure, high oil temperature, increased vibration, metal chip alarm	Lubrication link and secondary damage
rotor imbalance/blade damage	Mass eccentricity, blade cracks, friction, or impact from external objects	Increased vibration, spectral abnormalities, reduced thrust, and decreased EGT margin	The Chain of Evidence Based on Forensic Findings and Decisions Regarding Disassembly and Inspection
Foreign body aspiration/FOD	Bird droppings, sand, debris, tools, or fragments have entered the air passage.	Fan/compressor damage, vibration, reduced pressure ratio, thrust loss	Event Identification, Injury Assessment, and Emergency Decision-Making
Sensor drift/failure	Abnormalities in temperature, pressure, vibration, or flow measurement links	Single-parameter abnormality with multiple parameter inconsistencies; false alarm	Distinguish between actual faults and measurement errors.

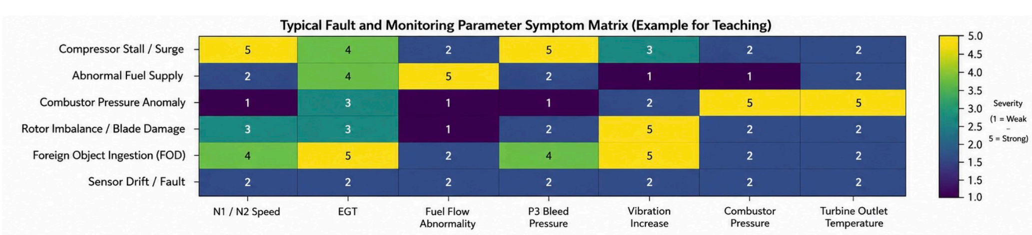

Figure 1. Signature matrix of typical faults and monitoring parameters.

The fault scenarios selected in this paper strictly follow three basic principles. The first principle is engineering representativeness. The selected faults cover the major subsystems of aero-engines, including the air system, control system, fuel supply system, lubrication system, and rotor system. Therefore, they are sufficiently representative for typical fault analysis [9].

The second principle is instructional clarity. Each fault phenomenon can be clearly explained using the basic concepts taught in the aero-engine principles course. This helps students connect theoretical knowledge with fault mechanisms and diagnostic reasoning.

The third principle is simulation feasibility. All selected faults can be represented through parameter models, 3D animations, alarm logic, and interactive experimental tasks. Based on these principles, this paper defines six typical fault categories [10].

The first category is compressor stall and surge, which usually result from abnormal operating conditions and cause significant fluctuations in engine parameters. This type of fault is suitable for multivariable experiments and helps students understand compressor structure, flow stability, and protection logic.

The second category is fuel supply abnormalities, which are usually caused by failures of fuel pumps, fuel metering components, nozzles, or control logic. These abnormalities may lead to thrust instability, difficult starting, acceleration delay, flameout, or overheating [11].

The third category is lubrication system failure, which can cause serious damage to bearings, transmission components, and rotor systems. Such faults are often reflected in abnormal oil pressure, oil temperature, and vibration signals.

The fourth category is rotor or blade damage. Rotor imbalance or blade damage changes aerodynamic performance and aggravates vibration and fatigue. Therefore, this type of fault requires comprehensive multiparameter diagnostic analysis [12].

The fifth category is foreign object damage (FOD). FOD can directly cause blade damage, airflow disturbance, thrust loss, and vibration increase. It is therefore an important fault scenario for virtual simulation experiments.

The sixth category is sensor malfunction. Although sensor faults may not directly damage the engine, they can lead to incorrect parameter readings, false alarms, or misleading diagnostic results. Therefore, they are also important for cultivating students' diagnostic judgment.

4. Overall design of the virtual simulation experiment project

The experimental setup adopts a dual-layer configuration by combining a general turbofan engine teaching model with a micro-turbojet bench parameter model. The general turbofan model provides a clear presentation of typical structural and airflow parameters of propulsion systems, while the micro-turbojet model supports experimental verification using available laboratory resources. This configuration facilitates the smooth integration of virtual simulation experiments with physical test benches.

Data processing tools such as LabVIEW and MATLAB are commonly used in university laboratories for operational testing, performance tuning, data acquisition, and fault analysis. Existing studies on micro aero-engine laboratories have carried out experiments on combustion instability, fuel line blockage, temperature anomalies, and shaft system imbalance, with particular attention to micro turbojets, turboshaft engines, and turboprop engines [13].

The overall architecture of this paper can be divided into six layers. The first layer is the 3D visualization layer, which supports structural understanding, transparent cross-sectional display, component labeling, and fault localization. The second layer is the physical model layer, which describes the basic functional relationships among thrust, temperature, pressure, rotational speed, fuel flow rate, and other physical quantities. It also includes simplified Brayton cycle models and component characteristic models.

The third layer is the fault injection layer, which defines fault types, component locations, occurrence times, and severity levels. The fourth layer is the data acquisition layer, which is responsible for collecting instrument data and presenting charts, alarm alerts, and data tables. The fifth layer is the diagnostic reasoning layer, which implements rule-based inference, threshold evaluation, trend analysis, residual analysis, and case-library comparison. The sixth layer is the evaluation and feedback layer, which automatically records students' operations, diagnostic processes, report quality, and reflective insights [14].

This paper proposes an implementable design philosophy of parameter-driven interaction, which goes beyond conventional animation-based demonstrations. When students adjust the throttle, change altitude, vary ambient temperature, or introduce a fault condition, the system immediately displays the corresponding responses in rotational speed, temperature, pressure, fuel flow rate, and vibration level. In this way, students can observe the relationship between parameter changes and engine operating states in real time.

Static animations alone may lead to a superficial understanding of engine fault mechanisms. Therefore, parameter interaction, dynamic response, and data logging should be integrated into the simulation process. Through these functions, students are encouraged to ask diagnostic questions such as: Why does the exhaust gas temperature first rise and then fall? Why does N_2 fluctuate when fuel flow remains relatively constant? Why do elevated lubricating oil temperature and increased vibration occur simultaneously? This training method is consistent with the engineering logic of aero-engine fault analysis [15].

5. Experimental content and task flow design

The paper presents three clearly stated and logically ordered experimental levels.

The first level is the Structural and Parameter Recognition Experiment. This experiment is designed to help students identify the engine intake, fan, compressor, combustion chamber, turbine, nozzle, fuel system, lubrication system, and sensor configurations. Since no complex faults are introduced at this stage, students can focus on basic operating parameters such as N1, N2, EGT, P3, fuel flow rate, and vibration. This helps them establish a fundamental understanding of the relationship among components, parameters, and energy conversion.

The second level is the Comprehensive Fault Diagnosis Experiment. In this experiment, students first observe baseline parameters under different operating conditions, such as normal startup, slow acceleration, rapid acceleration, cruise, and deceleration. Faults are then introduced either randomly or according to the instructor's instructions. Students are guided to analyze instrument data, trend curves, alarm signals, and three-dimensional fault location indicators.

Since the system does not provide direct answers, students are required to identify suspected faults, present supporting evidence, exclude similar faults, and propose appropriate remedial measures. For example, when a fuel filter clogging fault is simulated, students should observe restricted fuel flow, slow RPM response, insufficient thrust, and EGT fluctuations. Based on these responses, they can distinguish this fault from compressor surge or sensor failure alarms [16].

The third level is the Innovative Design Experiment, which focuses on multi-fault coupling and maintenance decision-making. This experiment is intended for senior undergraduates or graduate students. Typical coupled fault scenarios may include sensor bias, compressor efficiency degradation caused by foreign object damage, lubrication abnormalities leading to increased vibration, and blade damage causing performance degradation.

Students are required to complete a sequence of tasks, including data cleaning, residual analysis, fault tree analysis, maintenance priority ranking, and risk assessment. This experiment emphasizes that there is not always a single correct answer. Instead, the evaluation focuses on the sufficiency of evidence, logical consistency, and the reasonableness of maintenance strategies.

Each experiment follows a standardized six-step procedure. Step 1 is case introduction, in which the instructor presents a real accident or maintenance scenario, such as dual thrust loss caused by a bird strike, uncontained failure caused by fuel line fatigue, or thrust regression caused by restricted fuel flow. Step 2 is baseline parameter establishment, in which students record the normal ranges and trends of key variables under normal operating conditions.

Step 3 is fault injection, in which the occurrence time, affected components, and severity level of the fault are specified. Step 4 is diagnostic analysis, in which students examine multi-parameter evidence chains to determine the fault type. Step 5 is maintenance decision-making, in which students select appropriate actions, such as thrust reduction, engine shutdown, reset, return flight, component disassembly for inspection, or part replacement. Step 6 is report review, in which the system provides automatic feedback based on students' operational steps and submitted reports.

The experimental report template consists of six sections: experimental objectives, engine structure and parameters, fault phenomenon records, fault diagnosis process, troubleshooting plan, and reflections and improvements. To prevent students from simply stating conclusions, an Evidence Table should be included in the report. Students are required to list at least three supporting parameters and two exclusionary parameters.

Taking compressor stall as an example, supporting evidence may include a transient increase in EGT, rotational speed fluctuations, abnormal P3 changes, and thrust reduction. Exclusionary evidence may include the absence of sustained fuel supply insufficiency and no significant decrease in lubricating oil pressure.

6. Key models and data design

Since the fundamental challenge of virtual simulation experiments lies in ensuring model credibility, this paper proposes a modeling approach characterized by "a mechanism model as the framework, a rule base as the constraint, and data samples as supplementation." The mechanism model ensures that the basic directional relationships among variables such as temperature, pressure, rotational speed, fuel flow rate, and thrust are consistent with physical principles. The rule base defines fault trigger conditions, alarm thresholds, and diagnostic logic, while data samples enhance the realism and diversity of the generated curves.

For educational applications, the model does not need to fully replicate the exact control laws of a specific engine type. However, it must avoid parameter variations that conflict with thermodynamic principles or common engineering knowledge.

The steady-state performance model can establish relationships among variables such as total intake pressure, compressor pressure ratio, combustion chamber temperature rise, turbine power, and nozzle outlet velocity by simplifying the Brayton cycle. The transient model can describe the dynamic responses of rotational speed and temperature using first-order or second-order inertial links. Fault injection can be implemented by adjusting component efficiency, flow capacity, combustion efficiency, the upper limit of fuel flow, lubricant cooling capacity, or sensor offset.

Specifically, compressor contamination can be simulated by reducing compressor efficiency and flow capacity, thereby increasing fuel flow and decreasing the EGT margin under the same thrust requirement. Fuel filter clogging can be modeled by gradually lowering the upper limit of fuel flow over time, which consequently impairs the rotational speed response during acceleration.

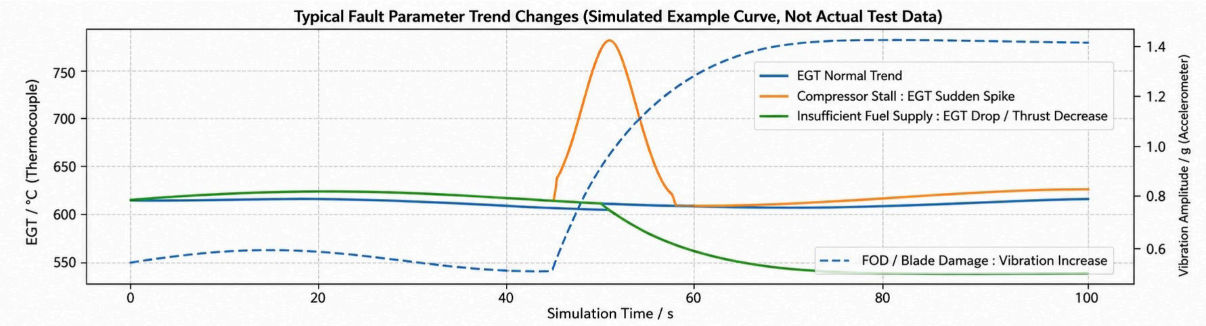

Figure 2. Example curve showing the variation trend of typical fault parameters (generated by virtual simulation, not actual equipment data).

7. Project implementation plan and teaching evaluation

Because the evaluation dimensions and their weightings have been clearly defined, the main assessment criteria for each component can be specified accordingly. Pre-class preparation and quizzes account for 10% of the total evaluation. This part is used to assess students' understanding of engine structure, thermodynamic cycles, common fault types, and key operating parameters.

Experimental procedures account for 20% of the total evaluation. This part evaluates students' ability to correctly conduct baseline recording, fault injection, curve observation, and safety-related operations. It also examines whether students can complete the prescribed experimental steps, record key parameters accurately, and operate the virtual platform according to safety requirements.

Diagnostic conclusions account for 15% of the total evaluation. This part focuses on whether students can identify the main fault types and fault locations based on the observed phenomena and parameter changes. Students are expected to explain their diagnostic conclusions rather than merely state the final answer.

The evidence chain and exclusion logic account for 25% of the total evaluation. This part requires students to provide multi-parameter supporting evidence and compare similar fault cases during troubleshooting. Students should explain why a certain fault is more likely than other possible faults and use parameters, curves, and theoretical knowledge to support their conclusions.

Disposal and maintenance recommendations account for 15% of the total evaluation. This part assesses whether the proposed sequence of actions is reasonable and whether it complies with safety limits and maintenance procedures. Students may propose measures such as continued monitoring, thrust reduction, system reset, return flight, shutdown, component inspection, or part replacement according to the severity of the fault.

Experimental reports and reflections account for 15% of the total evaluation. This part assesses the clarity of expression, the completeness of charts, the accuracy of data analysis, and the depth of reflection. Students should also explain the causes of any misdiagnosis and propose possible improvement measures.

The project implementation can be divided into three phases: pre-class preparation, in-class experiment, and post-class evaluation. Before class, students complete online preparatory learning on engine structure, thermodynamic cycles, and common fault mechanisms. Short quizzes are then used to check their mastery of basic concepts.

During class, instructors guide students through the virtual experimental environment. Students first collect baseline data under normal operating conditions and then work in groups to diagnose different fault scenarios. The experiment includes baseline recording, fault injection, curve observation, diagnostic reasoning, and safety handling.

After class, students submit experimental reports, which are evaluated by both the system and instructors. The evaluation focuses on diagnostic logic, parameter evidence, troubleshooting suggestions, report quality, and reflective insights.

The teaching method adopts the model of "individual practice + group discussion + class-wide review." Individual practice ensures that each student has the opportunity to complete the full experimental process independently. Group discussion allows students to compare different diagnostic sequences and reasoning methods. During the class-wide review, the instructor summarizes common misdiagnoses and reinforces key principles of multi-factor coupling.

For example, some students may attribute elevated EGT entirely to excessive fuel consumption without considering other possible causes, such as reduced compressor efficiency, turbine damage, or sensor drift. Therefore, the review session should guide students to analyze fault phenomena from multiple perspectives and avoid single-factor explanations.

The evaluation system should shift from outcome-based assessment to process-oriented evaluation. The diagnostic conclusion itself should not receive excessive weight, because real-world fault diagnosis often involves uncertainty. Instead, greater emphasis should be placed on the evidence chain, exclusion logic, troubleshooting strategy, and maintenance decision-making rationale. This encourages students to support their conclusions with appropriate parameters and theoretical arguments.

For innovative experiments, additional tasks such as data processing, fault tree modeling, and evaluation of maintenance decision rationale can be included. The system's automated evaluation function can record whether students have completed safety checks, established baseline parameters correctly, reviewed key curves, avoided high-risk operations, and drawn conclusions based on sufficient evidence. Instructors can then combine system records with report evaluation to assess students' engineering reasoning, presentation ability, and reflective thinking.

This evaluation method helps prevent virtual experiments from becoming simple "click-based passing exercises." Instead, it encourages students to develop analytical ability, diagnostic judgment, safety awareness, and engineering decision-making skills.

Because project quality improvement depends on continuous iteration, instructors should systematically identify the fault types with the highest error rates and the parameters most frequently neglected by students. The results can then be used to adjust instructional prompts, case difficulty levels, and assessment weightings. For example, if students have difficulty distinguishing an insufficient fuel supply from a compressor stall, comparative experiments should be introduced. If lubrication-related parameters are often neglected, the fault propagation animation should be improved to clearly show the relationship between bearings, rotors, oil temperature, oil pressure, and vibration.

Based on the evaluation criteria shown in Table 2, the learning evaluation of the virtual simulation experiment project can be organized around six dimensions: pre-class preparation and quizzes, experimental procedures, diagnostic conclusions, evidence chain and exclusion logic, disposal and maintenance recommendations, and experimental reports and reflections. This framework ensures that the assessment covers not only final answers, but also students' operating processes, reasoning logic, safety awareness, and improvement ability.

Table 2. Recommendations for learning evaluation of experimental projects

Evaluative dimension	Weight	Evaluation criteria
Pre-class preparation and quizzes	10%	Understand the engine structure, parameter meanings, and safety precautions.
Experimental Procedure	20%	Capable of performing baseline recording, fault injection, curve viewing, and security handling
diagnostic conclusion	15%	Capable of identifying major fault types and fault locations
Evidence Chain and Exclusion Logic	25%	Provide at least multi-parameter support evidence and similar troubleshooting evidence.
Disposal and Maintenance Recommendations	15%	The disposal sequence is logical and complies with safety boundaries and maintenance requirements.
Experimental Report and Reflection	15%	The presentation follows standardized norms, includes complete charts, and clearly explains the reasons for misjudgments as well as improvement measures.

8. Project features and innovations

The simulation project has five key characteristics. First, it constructs a fault causality network based on real failure mechanisms. Second, it integrates authentic aviation accident cases into the fault diagnosis process. Third, it employs multi-parameter analysis to build fault evidence chains, thereby aligning with the development trends of modern diagnostic technologies. Fourth, it adopts a hierarchical and scalable platform architecture to meet diverse teaching and research needs. Fifth, it incorporates engineering ethics education and visualized safety boundaries.

9. Expected application outcomes and promotion value

The project significantly enhances teaching effectiveness by helping students master engine principles, improve fault analysis skills, and optimize the utilization of experimental resources. Through a blended virtual-real learning approach and interdisciplinary course integration, it provides an effective platform for cultivating versatile aviation professionals. In addition, it strongly supports students' scientific research activities.

10. Conclusion

This paper provides a clear and structured discussion of the "Design and Exploration of a Virtual Simulation Experiment Project for Typical Fault Analysis in Aero-Engines." It first proposes a virtual experiment framework that integrates aircraft engine principles, engine structure, control systems, maintenance, and health management. Based on typical fault mechanisms and a multi-parameter evidence chain methodology, the study uses 3D visualization and parametric simulation to establish a complete experimental workflow: structural analysis, parameter monitoring, fault injection, diagnostic reasoning, troubleshooting decision-making, and report evaluation.

The analysis shows that developing virtual simulation experiments for typical aircraft engine fault analysis is not merely a matter of improving visual effects. Its fundamental objective is to ensure accurate fault mechanisms, reasonable parameter responses, complete task chains, and clear evaluation criteria. Therefore, it is appropriate to incorporate various fault scenarios, including compressor stall, fuel supply abnormalities, lubrication system failures, rotor imbalance, foreign object ingestion, and sensor drift.

Future improvements can be pursued in three key directions. First, real-world micro-engine test bench data can be integrated to enhance model credibility. Second, machine learning and interpretable diagnostic algorithms can be incorporated to improve the intelligence of the system. Third, teaching-based empirical research methods can be used to evaluate actual improvements in students' fault analysis skills through indicators such as pre- and post-test performance, learning behavior data, and experimental report quality.

Overall, this project provides a practical, safe, cost-effective, reproducible, and scalable solution for practical aviation engine education. It can also serve as a valuable reference for the digital transformation of experimental teaching in aerospace disciplines.

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