Model-Based Fault Identification of Fighter Aircraft's Environmental Control System

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ABSTRACT

The Environmental Control System (ECS) maintains conditions suitable for a crew inside aircrafts cabin. ECS controls temperature, pressurizes cabin, provides breathing air and removes excess air humidity. All ECS functionalities have great impact on pilots' safety, performance and comfort. Furthermore, aircrafts mission capability is largely dependent on ECS.
Since ECS working principle is relatively complex, fault detection or fault identification can be very challenging. Most common failures are relatively easy to identify and trace to a specific component. Challenges however arise from complex interactions inside ECS, where single valve or sensor can affect to a whole system and cause undesirable and unknown phenomena. To better understand these complex interactions, comprehensive calculations or simulations are needed. When considering the complexity of ECS, computer modeling turns out to more suitable option than conducting multiple complex calculations.
Objective of this project was to improve fault identification process with semi-empirical model of the specific military fighter jet. Moreover, aim was to acquire more profound knowledge of the system and its characteristics. Modeling provided new way of studying ECS system, it flaws and potential failures. Model was created to answer questions that could not be tested on a test bench or on ground-tests. Basically, modeling enabled possibility to virtually test multiple different scenarios and their probability. Project resulted partially verified AMESim model of the ECS, which can be considered valid in most of the common flight situations. ECS-model helped to narrow down possible causes of undesirable behaviour that was known to occur in specific flight situation. ECS-model basically clarified the underlying phenomena leading to these undesired events.
In future, model's reliability and accuracy will be enhanced with new comprehensive measurements. Model will also be transformed to simplified version which can be used to train new maintenance engineers.

KEYWORDS: *Environmental control system, ECS, fighter, jet*

1 INTRODUCTION

Fighter aircraft's environmental control system (ECS) have a major impact on pilot safety and aircraft mission capability. ECS maintains conditions suitable for crew inside aircrafts cabin by pressurizing cabin, regulating temperature and providing breathing air. ECS can also be used for: avionic cooling,

defog, anti-ice, muscle pressure, anti-G, reservoir pressurization and gun gas purge. Without fully functional and robust ECS, aircraft is unable to function properly and carry out missions safely. All of the ECS' functionalities are essential for aircraft's airworthiness, which addresses the importance of maintenance, fault isolation and fault identification.
Most of ECS' include only minimal amount of sensors monitoring it's operation during flight. Therefore aircraft ECS failure modes can usually be tested only on the ground. In most of the cases aircrafts failure modes can be identified and solved during ground testing. But, some of the problems only occur during flight, even if the aircraft has passed ground testing. In addition, ECS working characteristics change drastically during flight when compared to ground operation. Without additional tools such as computer modeling, troubleshooting of flight situations is beyond challenging. Simulations provide new information which otherwise could not be collected.
In this project, a semi-empirical simulation model was constructed in order to aid the fault identification process of fighter jet's ECS. Model was also designed for testing of multiple theories, regarding the causes of specific failure modes. Model is designed to work on both dynamic and steady-state simulations. Almost entire ECS needed to be modelled so that complicated interactions could be studied. Ultimately, the goals were to study ECS' dynamic response in multiple flight situations, estimate how well ECS performs in aircrafts flight envelope and how ECS reacts to different component failures.

2 ECS SYSTEM DESCRIPTION

Fig. 1 presents the simplified process diagram of the ECS. Hot air is bleeded from two jet engines and cooled down with reversed Brayton cycle. Some of the bleed air bypasses cooling cycle and is then utilized to control cabin supply air temperature as well as avionic cooling temperature. System uses air-to-air heat exchangers for cooling. Excessive humidity is extracted in high pressure water extractor and condensed water augments cooling in secondary heat exchanger.

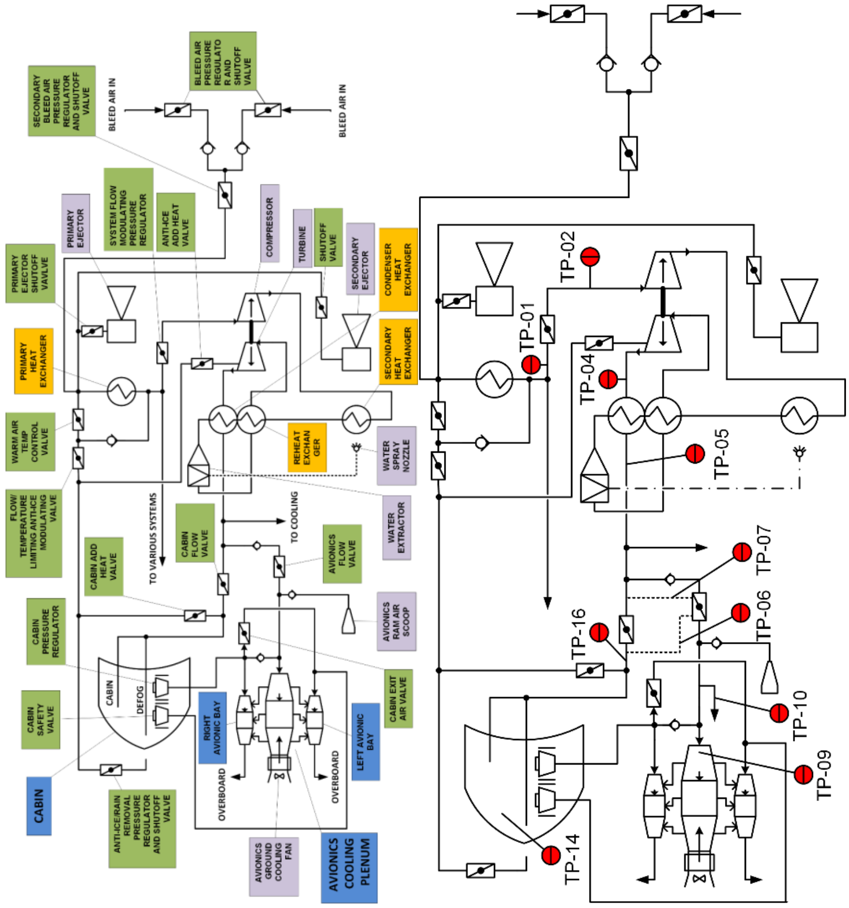

Figure 1: Simplified schematic of the complete ECS (left) and test port locations (right) [1]

The ECS controls mass flow, temperature and pressure in both cabin and avionic bays. Supply airs mass flow amount and temperature changes according to altitude and flight speed. One fully mechanical valve controls the cabin pressure by regulating the mass flow amount that flows overboard. Avionic bays are not pressurized hence pressure is near ambient.

3 STATE OF THE ART IN ENVIRONMENTAL CONTROL SYSTEM MODELLING

Modeling ECS and its complicated dynamic behavior is not unprecedented. Probably one of the first was Eichler (1975), who modelled whole ECS and studied its dynamic response [1]. Eichler already used multiple simplified models of controllers, sensors, valves and turbines. Since Eichler's study, computer modeling has evolved along with increasing computing power. Later studies have used modeling dynamic response from multiple slightly different standpoints. Tu and Lin (2010) modelled ECS using Flowmaster software and studied the thermal dynamic response of the ECS [2]. Tu and Lin (2011) further developed their simulation model and used it to improve ECS' control system [3]. Yin et al. (2016) used a simplified model of the ECS to study dynamic response, coupled with CFD based cabin thermal model [4]. Their study showed interaction between ECS operation and cabin thermal conditions.

Because of unpredictable and complicated behavior of ECS, many studies have gravitated more towards hardware-in-the-loop approach. If only computer based models are used, things like ice formation and two-phase flow are very hard to take into consideration and may ultimately lead to misleading results. To minimize the effect of unpredictable phenomena, Childs et al. (2015) used hardware-in-the-loop method and constructed full scale experimental and simulation tool for control system optimization and fault detection [5]. Childs et al. (2016) later used testing facility to investigate multiple failure modes and their effects [6]. Similar fashion Ashford (2004) utilized hardware-in-the-loop approach to study the f-22 raptors ECS responses and developed ECS' controlling software further [7].

Unlike Childs et al. (2016) and Ashford (2004), this study relies only on semi-empirical computer modeling. However, model validity is tested against multiple measurements conducted with physical aircraft. Hardware-in-the-loop method is simply troublesome to implement when flight at high altitude is one of the interests.

4 MODELLING THE ENVIRONMENTAL CONTROL SYSTEM

Semi-empirical model of ECS was etablished using LMS Imagine.Lab Amesim rev. 13. Amesim enables to model, simulate and analyze multi-domain systems. It has a wide range of component libraries that can be used to model ECS. Final model consists of Amesims standard library parts [9].

Parameters had to be resolved using real-life measurements. Component parameters were resolved by using a wide variety of measurements. Components' sizes and shapes were measured to match the Amesim submodel requirements. Some of the measurements were conducted by the manufacturer of the aircraft during its development e.g. ram air flow, heat exchangers' cooling effectiveness, compressor and turbine characteristic curves.

Model's validity in steady state situations, was tested by comparing simulation and ground test results. During a ground test, pressures inside ECS can be measured from 10 different test ports and temperatures from 4 points (cabin, avionics, louver and primary heat exchanger). Neither the pressure nor the temperature sensors can detect transient changes.

Model's accuracy in dynamic situations was studied against measurements. Aircraft was flown in many flight situations while data logger (MSR Electronics GmbH, model 145) recorded temperatures and pressures inside the cabin. Also, aircraft's flight recorder data was collected and then used as an input to the simulation model. Measurements in cabin were then compared to simulated results. Model of the ECS control system was altered in iterative process till results were comparable.

5 STEADY STATE SIMULATIONS AND RESULTS

In Table 1–4 model's steady state accuracy is presented. Both measurement and simulation data represent pressures during ground testing. Simulation results are compared to measurements in four different throttle settings (high throttle, medium throttle, idle and manual-mode). Test port locations are shown in Fig. 1.

Table 1: Comparison of simulation results with measurements in high throttle

Test port	*Measurement [barA]*	*Simulation result [barA]*	*Error [barA]*
TP-01	9.388	9.358	0.030
TP-02	2.631	2.658	0.026
TP-04	1.185	1.347	0.162
TP-05	1.177	1.147	0.030
TP-06	1.102	1.079	0.023
TP-07	1.165	1.142	0.023
TP-09	1.066	1.000	0.067
TP-10	1.001	1.013	0.012
TP-14	1.036	1.015	0.021
TP-16	1.104	1.079	0.025

Table 2: Comparison of simulation results with measurements in medium throttle

Test port	*Measurement [barA]*	*Simulation result [barA]*	*Error [barA]*
TP-01	6.356	6.317	0.040
TP-02	2.702	2.647	0.055
TP-04	1.149	1.359	0.210
TP-05	1.142	1.153	0.012
TP-06	1.049	1.085	0.036
TP-07	1.130	1.149	0.019
TP-09	1.045	1.001	0.044
TP-10	1.000	1.013	0.013
TP-14	1.041	1.020	0.020
TP-16	1.056	1.086	0.030

Table 3: Comparison of simulation results with measurements in idle

Test port	*Measurement [barA]*	*Simulation result [barA]*	*Error [barA]*
TP-01	2.013	2.029	0.016
TP-02	2.082	2.022	0.060
TP-04	1.140	1.258	0.118
TP-05	1.138	1.152	0.014
TP-06	1.076	1.088	0.012
TP-07	1.132	1.151	0.019
TP-09	1.066	1.001	0.065
TP-10	1.031	0.988	0.044
TP-14	0.993	1.022	0.030
TP-16	1.080	1.088	0.007

Table 4: Comparison of simulation results with measurements in manual-mode

Test port	*Measurement [barA]*	*Simulation result [barA]*	*Error [barA]*
TP-01	4.425	4.381	0.044
TP-02	4.494	4.331	0.163
TP-04	1.390	1.720	0.330
TP-05	1.383	1.329	0.054
TP-06	1.082	1.147	0.065
TP-07	1.342	1.315	0.028
TP-09	1.272	1.025	0.247
TP-10	1.032	1.059	0.027
TP-14	0.995	1.052	0.057
TP-16	1.100	1.147	0.047

Model is accurate in all ground test cases. The only notable problem occurs in TP-04 pressures which are greater than experimental results suggest. Two different things may cause pressure rise in simulated results. Either condenser heat exchanger gives too high flow resistance and causes pressure rise upstream, or simulated control system mixes too much warm air to the turbine downstream and causes pressure rise. Also, both sources of error may occur simultaneously. More measurements are needed to increase accuracy.

6 DYNAMIC SIMULATIONS AND RESULTS

Model's accuracy in dynamic simulation is shown in Fig. 2. The aircraft was flown at 45,000 feet altitude while throttle was altered rapidly to cause prominent pressure fluctuation. Simulation results represent measurements well. However, model only works at this specific altitude. If flight altitude changes more than 3,000 feet, measurements and simulation results start to differ. Control system's parameters must be tuned to different altitudes so that measurements and simulations are equivalent. Also, regardless of the flight altitude, computer model reacts to changing throttle position slower than the real system.

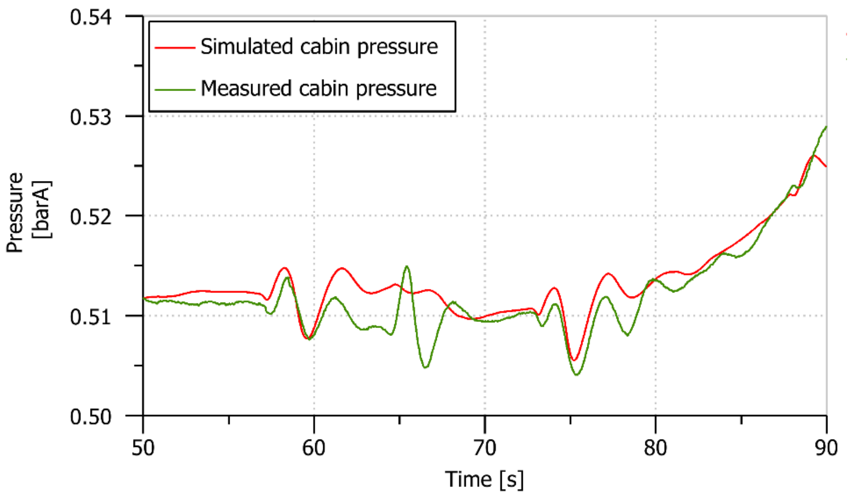

Figure 2: Cabin pressure at 45,000 feet altitude during rapid throttle alternation

In dynamic simulation shown in Fig. 2, simulated control system had to react on a distinctive way so that results matched with empirical measurements. In other words, valves must react in a specific order and speed. Otherwise, pressure curve will not form its characteristic shape. So, it can be concluded with high confidence that simulation represents reality very well. Therefore, highly tuned simulation model gave knowledge of how exactly control system reacts and how valves must be moving. Knowledge of the valve interactions may turn out to be important, especially if aircraft suffers from cabin pressure fluctuation.

As the dynamic simulations gave promising results, model was also used for predicting the outcome of a component failure. One concern was the effect of a cabin exit air valves (shown in Fig. 1) and its effect on cabin pressure at 45,000 feet altitude. Cabin exit air valve was controlled from closed position to fully open position and back to fully closed position. Then valve's effect to cabin pressure was studied (Fig. 3). Simulation results suggest that cabin exit air valve cannot solely cause severe failure, since pressure change is very small. Cabin exit air valve did not cause significant change to mass flows either.

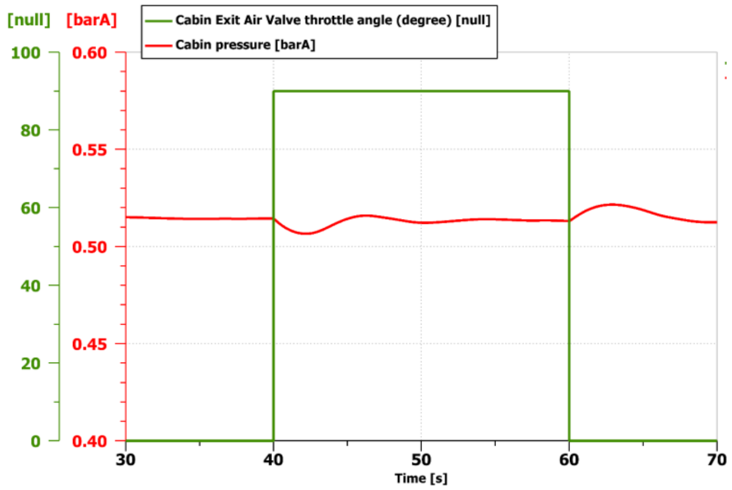

Figure 3: Cabin exit air valves effect to cabin pressure at 45,000 feet altitude.

Steady state accuracy during a flight is yet uncertain, since ground testing does not necessarily represent more complicated flight situations. Dynamic simulations gave promising results, though model had to be tuned to specific altitude and universally valid model could not be accomplished. Nonetheless, dynamic simulation accuracy enabled the ability to test and predict effect of a certain failures.

More empirical measurements are needed to further increase model credibility. Transient pressure and temperature changes must be measured inside the system during ground testing and flight. Only then the model's validity in multiple flight situations can be estimated with confidence. ECS valve interactions are simply too complicated to simulate with existing knowledge.

7 CONCLUSION

In this study model of an aircraft ECS was constructed using LMS Imagine.Lab Amesim rev. 13. Model's accuracy was verified against measurements of ground testing in steady state situation. Furthermore, model validity was tested in dynamic flight situation by comparing measured and simulated data. Finally, model's capability to predict outcomes of component failure was presented.

Steady state results were comparable with empirically measured data. The only significant difference occurred in test port TP-04. New measurements are needed to determine the clear cause of pressure difference in TP-04.

Results in dynamic flight situation were satisfactory and provided new knowledge of the ECS response characteristics. Simulation of dynamic response is valid only at one specific altitude at a time. More precise measurements inside the ECS are needed to increase model credibility.

Model ability to predict the outcome of cabin exit air valve failure was demonstrated in this study. It can be concluded that cabin exit air valve solely cannot cause severe pressure fluctuation or mass flow change in the cabin.

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