

A Specification Analysis Framework for Aircraft Systems

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ABSTRACT

Future aircraft systems are projected to have order of magnitude greater power and thermal demands, along with tighter constraints on the performance of the power and thermal management subsystems. This trend has led to the need for a fully integrated design process where power and thermal systems, and their interactions, are considered simultaneously. To support this new design paradigm, a general framework for codifying and checking specifications and requirements is presented. This framework is domain independent and can be used to translate requirement language into a structured definition that can be quickly queried and applied to simulation and measurement data. It is constructed by generalizing a previously developed power quality analysis framework. The application of this framework is demonstrated through the translation of thermal specifications for airborne electrical equipment, into the SPecification And Requirement Evaluation (SPARE) Tool. The SPARE Tool is a MATLAB toolbox that automates both the thermal and power quality analysis of simulation and experimental data based on the techniques discussed in this paper. The combination of both thermal and power quality analysis into one tool, demonstrates how a single program can be used to analyze requirements across both power and thermal systems. A sample inverter design problem is used to illustrate how the SPARE Tool can be used to analyze thermal requirements and identify potential design compromises between the electrical and thermal domains. This example shows the value of multi-domain analysis programs, like the SPARE Tool. Use of such tools will enhance collaboration, speed up design iterations, and aid engineers and researchers in meeting the design challenges of future aircraft systems.

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INTRODUCTION

The development of next generation aircraft systems is an increasingly interdisciplinary process with designs needing to simultaneously consider constraints from multiple domains. This is a consequence of the growing demand for electrical power and thermal cooling in aircraft. Future aircraft systems are projected to have order of magnitude greater power and thermal demands than current platforms [1]. These increasing demands are necessitating the development of novel technologies that push the boundaries of power and thermal constraints. For example, in order to reduce the cooling demand of power electronics, silicon carbide semiconductors are being developed which can operate at temperatures in excess of 400°C. Such devices may not require the use of forced air- or liquid-cooling which could significantly impact aircraft cooling topologies [2, 3]. In this highly constrained environment, the traditional watershed approach to system design is insufficient. Rather an integrated design environment is needed where engineers and researchers from multiple disciplines (electrical, mechanical, controls, etc.) can analyze potential designs against specifications and requirements from a variety of domains. To enable this level of collaboration, it is helpful to have a common tool which can be used across multiple disciplines. To that end, a

general framework is presented for codifying and organizing specifications and requirements into a single software tool. This framework is independent of the analysis domain. Finally, a tool for the combined analysis of power quality and thermal specifications of airborne electrical equipment is presented which was constructed using this framework.

The development of the framework and multi-domain analysis tool began with an examination of the previously developed Power Quality Analysis Tool (PQATool). This tool was developed to automate the process of applying the power quality specifications given in MIL-STD-704 along with the electromagnetic interference specifications in MIL-STD-461F CE102 [4, 5]. When developing the PQATool, several techniques were used to interpret and standardize the transient, steady-state, and frequency power quality specifications given in MIL-STD-704 and a discussion of those techniques can be found in [6, 7]. Using this tool, one can analyze a variety of AC and DC signal attributes which are summarized in Table 1. For the development of the general specification and requirement checking framework, the structure of the PQATool was used as a foundation. From this foundation, a domain independent process of interpreting and organizing specifications was developed.

Using this process, a thermal specification tool is constructed from MIL-STD-2218: Thermal, Design, Analysis, and Test Procedures for Airborne Electrical Equipment. This standard defines temperature constraints, humidity constraints, coolant pressure and mass flow requirements, and transient thermal specifications for normal and abnormal operation of aircraft electrical equipment [8]. While both MIL-STD-704 and MIL-STD-2218 apply to aircraft electrical systems, they constitute very different types of analysis using different specifications and time-scales. However, with the specification and requirement checking framework, both analysis tools are able to be combined into one multi-domain tool. Furthermore, this tool can be easily expanded to include additional specifications and domains.

Table 1. AC and DC signal attributes which can be evaluated using the PQATool [6, 7].

DC	AC
Average	Crest Factor
Distortion	DC Component
Distortion Factor	Distortion
Frequency Error	Distortion Factor
Frequency Response	Frequency Drift
Ripple	Frequency Error
RMS	Frequency Modulation
Transient: Abnormal	Frequency Response
Transient: Normal	Load Unbalance
Transient: Source Transfer	Phase Difference
	RMS
	Transient: Abnormal
	Transient: Normal
	Transient: Peak
	Transient: Source Transfer
	Voltage Modulation
	Voltage Unbalance

The remainder of this paper is divided into four main sections. First a summary of MIL-STD-2218 is provided along with a mathematical interpretation of its requirements. Then, the general framework for specification and requirement checking is discussed, using instances from MIL-STD-704 and MIL-STD-2218 as illustrative examples. Next a software tool that combines the analysis of MIL-STD-704 and MIL-STD-2218 into one interface is presented and demonstrated through the analysis of an inverter model. Finally, concluding remarks and suggestions for future work are provided.

SUMMARY OF MIL-STD-2218

This section summarizes the main definitions and requirements given in MIL-STD-2218. The primary purpose of this specification is to define the thermal operating conditions and events that airborne electrical equipment should be designed to operate in without any manual adjustment. This specification requires that airborne electrical equipment operate satisfactorily within the temperature-altitude environment defined for class 2 systems, shown in Figure 1 [9]. Approximations for the boundary curves are given by Eq. (1) and Eq. (2). In addition, this specification can be used as a guide when

selecting the appropriate cooling method for a piece of equipment. The preference is to 1) use ambient cooling, 2) use air from the environmental control system for forced air-cooling and 3) use alternate cooling methods [8]. Therefore, the operational and transient thermal specifications given below are further subdivided into which cooling method to which they apply.

$$T_A = 0.0034\alpha^3 - 0.22\alpha^2 + 0.23\alpha + 71$$

For $0 \leq \alpha \leq 21.28$

(1)

$$T_B = 0.0031\alpha^3 - 0.2\alpha^2 + 0.3\alpha + 95$$

For $0 \leq \alpha \leq 21.28$

(2)

Here T_A and T_B are the boundary temperatures, in °C, of the continuous and intermittent operating regions, and α is the altitude in km.

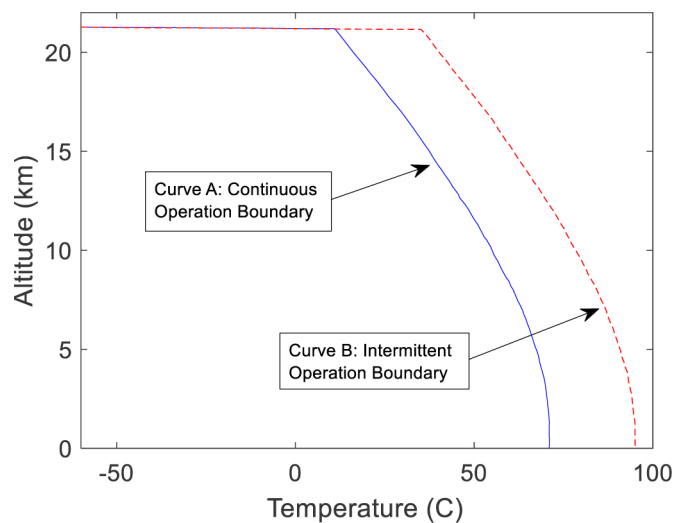


Figure 1. Temperature vs. altitude operating range for class 2 equipment. Equipment should be designed to operate continuously within curve A and for up to 10 mins between curve B and A.

Definitions

The requirements given in MIL-STD-2218 use several key words whose definitions are essential to interpreting the meaning of the requirement. The definitions of the key terms which are used in this paper are provided below. All of these definitions are paraphrased from MIL-STD-2218.

Ambient Cooled Equipment

Equipment dissipates its heat to the ambient environment, which can include the use of fans or blowers to circulate the ambient air.

Design Flow Rate

The minimum flow rate required to maintain component temperature within the specified requirements.

Detail Equipment Specification

A specification that establishes the performance, design, development, installation, test, and demonstration requirements for the equipment and sets forth operational and environmental requirements for its intended use.

Forced Cooled Equipment

Equipment dissipates its heat to gas, including air or ram air, or liquid supplied by vehicle subsystems with sufficient pressure to flow through the unit.

Stabilization

The temperature of the component with the largest thermal time constant varies at a rate less than 2 °C per hour.

In addition to the above definition, MIL-STD-2218 defines several thermal operating modes for airborne electrical equipment.

Abnormal Operation

Equipment is operated through normal duty cycle at maximum voltage with a loss of coolant, or increase in ambient temperature, or both for a period of time not exceeding 10 mins. *Intermittent operation* is a special case of abnormal operation in which the equipment is operated at nominal voltage and the ambient temperature change is to the intermittent region of Figure 1. *Emergency cooling* is an abnormal operating mode in which coolant flow is equal to 75% of the design flow rate for 30 min.

Normal Operation

Equipment is operated through its normal duty cycle at nominal voltage. *Continuous operation* is a steady state normal operation. *Ground operation* is normal operation at sea level (14.7 psia $\pm$ 5%, 15 °C $\pm$ 1 °C).

Start-Up Operation

This is a transient condition in which equipment and external cooling mechanisms are initially off. Then the equipment is operated through its normal duty cycle at nominal voltage. The condition ends when stabilization has occurred.

Operational Requirements

When analyzing the performance of analytical models or experimental data of airborne electrical equipment for compliance with MIL-STD-2218, there are three main operational metrics to consider:

1. Component Temperature
2. Design Coolant Flow Rate
3. Coolant Flow Pressure Drop

Component and part temperatures must remain within the specified temperature ranges that satisfy their reliability requirements. For final production designs, these temperature ranges should be determined from a thermal and reliability design analysis and provided in the

detail equipment specifications. For components that lack this detailed analysis, MIL-STD-2218 provides the general temperature guidelines shown in Table 2.

Table 2. Preliminary allowable junction temperatures from MIL-STD-2218.

Operating Condition	Microcircuits	Power Devices
Normal	105 °C	125 °C
Abnormal	115 °C	150 °C

For components that are forced air- or liquid-cooled, the cooling system must satisfy the design flow rate requirement. The design flow rate is the minimum flow rate required to keep the component, and all parts, within the required temperature bounds. This requirement is heavily dependent upon the amount of heat that must be absorbed by the coolant and the allowable temperature change in the coolant. To visualize this relationship, one can plot the coolant mass flow rate per kW of heat absorbed vs. the allowable coolant temperature change. The scale of this relationship depends on the specific heat of the coolant. Figure 2 shows this relationship for air, Polyalphaolefin (PAO) and water.

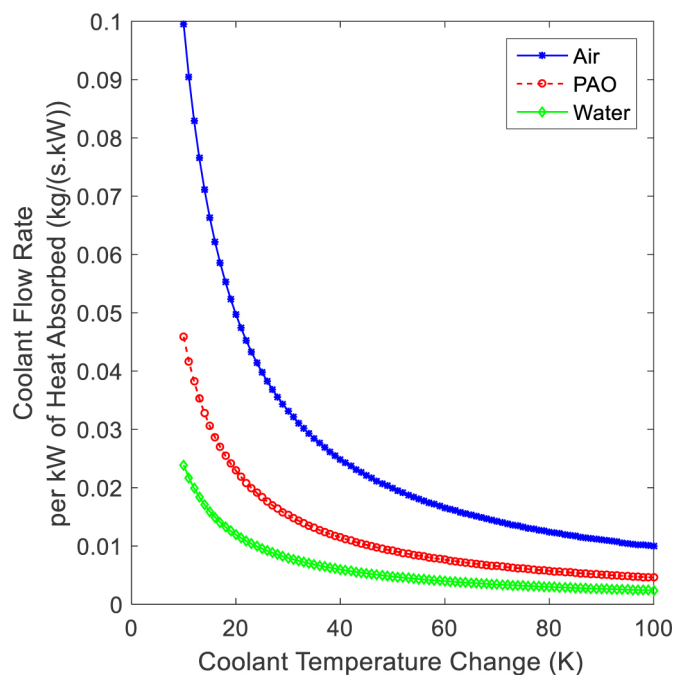


Figure 2. Coolant flow rate per kW of heat absorbed vs. coolant temperature change for air, PAO, and water at standard temperature.

Here one can see that as the magnitude of the allowable temperature change decreases, the required coolant mass flow per kW of heat absorbed increases. The allowable coolant temperature change is dependent upon the allowable coolant discharge temperature and the coolant inlet temperature. From MIL-STD-2218, the allowable discharge temperature shall not exceed 71 °C and should be determined from the life cycle cost and reliability requirements of the electrical component. The coolant inlet temperature is not a parameter that can be given as a specification, since it will vary during operations and will be a function of the other loads on the system. Therefore, for each kind of forced cooling and for different operating