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Control System Development Experience for Aero Gas Turbine Demonstrator Engines

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Abstract. The unique development project requirements of a gas turbine engine [GTE] dictated the concurrent design, development and integration of the control system and the GTE. Valuable development experience was obtained from testing of various engine configurations. Subsequently, this enabled a prescription of system requirements for a flight worthy full authority digital electronic control [FADEC] system. This approach had to meet the mandatory requirements of independent verification and validation [IV and V] of control system that were laid down for military engine applications. The FADEC system was successfully configured, developed and integrated with the gas turbine engine on this basis.

Keywords: Control system, Gas Turbine Engine, Hydromechanical System, Full Authority Digital Electronic Control, Verification and Validation

Nomenclature

FADEC: Full Authority Digital Electronic Control
FMECA: Failure Mode Effects and Criticality Analysis
GTE : Gas Turbine Engine
GTRE : Gas Turbine Research Establishment
GTX : Gas Turbine Experimental
IV& V: Independent Verification and Validation
PLA : Power Lever Angle, Pilot Lever Angle
SOR : Statement of Requirements
T1 : Compressor Inlet Total Temperature

1. Introduction

The 1930's saw the evolution of independent design and development work on gas turbine engines in Great Britain and Germany. Sir Frank Whittle patented his gas turbine engine in 1930 and after several years of development, a version of the same was first installed in an aircraft in 1941 [1]. Hans von Ohain had a patent for his engine in Germany in 1936 and the first flight with this engine had taken place in 1939 [1]. The first GTE as developed by Whittle [2, 3] had a simple throttle lever that controlled fuel flow into the engine. The technical aspects of Whittle's pioneering work in gas turbine development have been described in great detail by Meher-Homji [4].

To accommodate the functional requirements when fitted in aircraft, design of fuel control system had to take into account effects of altitude, temperature and forward speed [5, 6]. At the same time, continued requirements to improve GTE performance, production and lifing processes had their impacts on gas turbine technologies [7]. In order to introduce redundancy and enable greater safety in operation, certain electric supervisory devices and limiter controls were introduced [8]. The subsequent growth of electronics and computer technology with their enhanced reliability enabled full authority digital electronics to be used [9]. A historical perspective of the advancement in control technologies for aircraft gas turbine engines related to the US scenario has been outlined by Jaw and Garg [10]. In the Indian scenario, a challenging task taken up in the 1970's was the design and development of a twin spool gas turbine demonstrator project called the Gas Turbine Experimental [GTX] [11]. A simple engine speed-power lever angle loop is illustrated in Figure 1.

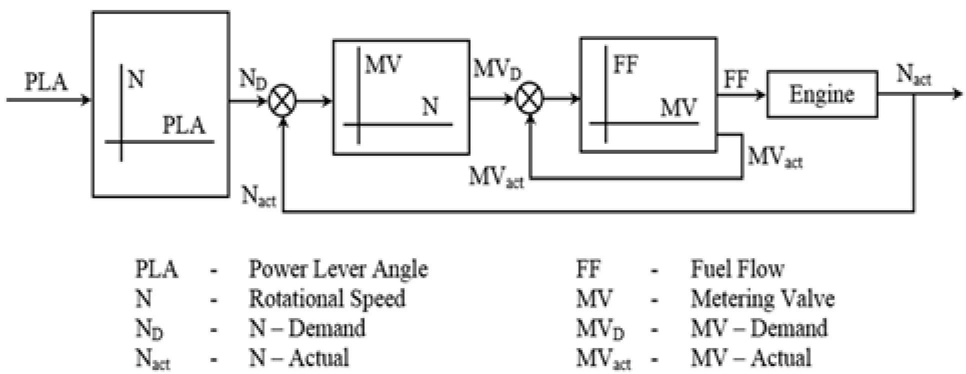

Figure 1: Typical engine speed-Power Lever Angle (PLA) loop

The development and integration aspects of the control system in the different phases of the above demonstrator engine program posed interesting challenges. The initially used conventional mechanical control system brought out the limitations and inflexibility of integrating such a system with an engine system under development. The initial experience with data capture and converting into system performance plots has been brought out [12]. The early steps for conducting simulation of hydromechanical fuel control had also been launched [12, 13]. A bottom to top approach of understanding the updated engine requirements and consequent changes/reconfiguration in control system over the complete thrust range of this engine thus emerged.

Considering the limitations of a mechanical system and developments in the world scenario [14,15,16,17,18,19,20,21,22,23,24,25,26,27,28,29& 30], a proposal for a full authority digital electronic system ahead of an advanced GTE program had set the vision for the right technological approach. The design inputs for this system had to take into account the form, fit and functional requirements for integration with an aircraft [31]. The important tools and aids that were found critical for development testing and integration of control systems with engines were rig and simulation facilities [31, 32 and 33]. With the increasing content of software and its modules, there had been a greater need for verification and validation of software. Adherence to prescribed Design and Certification standards was required. This ensured traceability of all information from design to final acceptance so that aspects related to system requirements, design adequacy, manufacturability/assembly/test, coding, FMECA, lifing, safety, etc., were completely verified and validated through suitable resources. This mandated the top to bottom flow of specifications from engine to control system. This needed support of dedicated test facilities, methodologies and system/sub-system level review teams as a precursor for independent verification and validation.

2. Bottom to top system integration-hydromechanical system

Basically, the GTE required control of fuel flow to operate the engine for it to achieve the specified performance and within the limits of pressures, temperatures, vibration levels and clearances prescribed for the engine. The philosophy and approach involved in the design and configuration of the fuel control systems has been well brought out by Watson and Lawrence [5, 6].

3. The transition phase from hydromechanical to electronic systems

Mechanical control systems when integrated with demonstrator GTE suffered from the inherent limitations of tuning and adjustment beyond their physical defined limits. The electronic software based control thus offered distinct advantages, such as: Ease of adjustments of transient schedules/ limiter schedules/Magnitude changes and slope changes in schedules/Changes in control logics. All these could be accomplished by changes of software build of the embedded controller in the electronic system [34]. Based on the redundancy management architecture, safe operation even with one lane non-operational could be demonstrated.

At the start of the gas turbine era, there had been only one control variable, namely, fuel flow. With advances in gas turbine cycles and technologies, the need for a greater number of control variables had slowly evolved over the decades. The typical growth of control variables over the initial decades is illustrated by Szuch [35]. Variable area nozzle control in the Indian context was illustrated by Arun Prasad [11].

4. Top to bottom approach of system integration with electronic systems

In the bottom to top approach of engine design and development the functional and integration aspects had been understood. While launching the FADEC system project for the next candidate engine configured around a specified airframe, a total system approach had to be followed. To meet the rigorous performance and safety requirements of the engine, airframe installation and the certification authorities, a detailed program in line with Military Standards [36] had to be specifically followed. This called for a clear system development cycle approach from the stage of capture of System Requirements up to the stage of final certification and acceptance of hardware and software configuration items. An overall typical approach is illustrated in Figure 2 [36]. Review process in line with Military Standards [36] also had to be undertaken. The audits that were outlined in the interim stages are also indicated. The schematic evolved for the FADEC system was typically as in Figure 3.

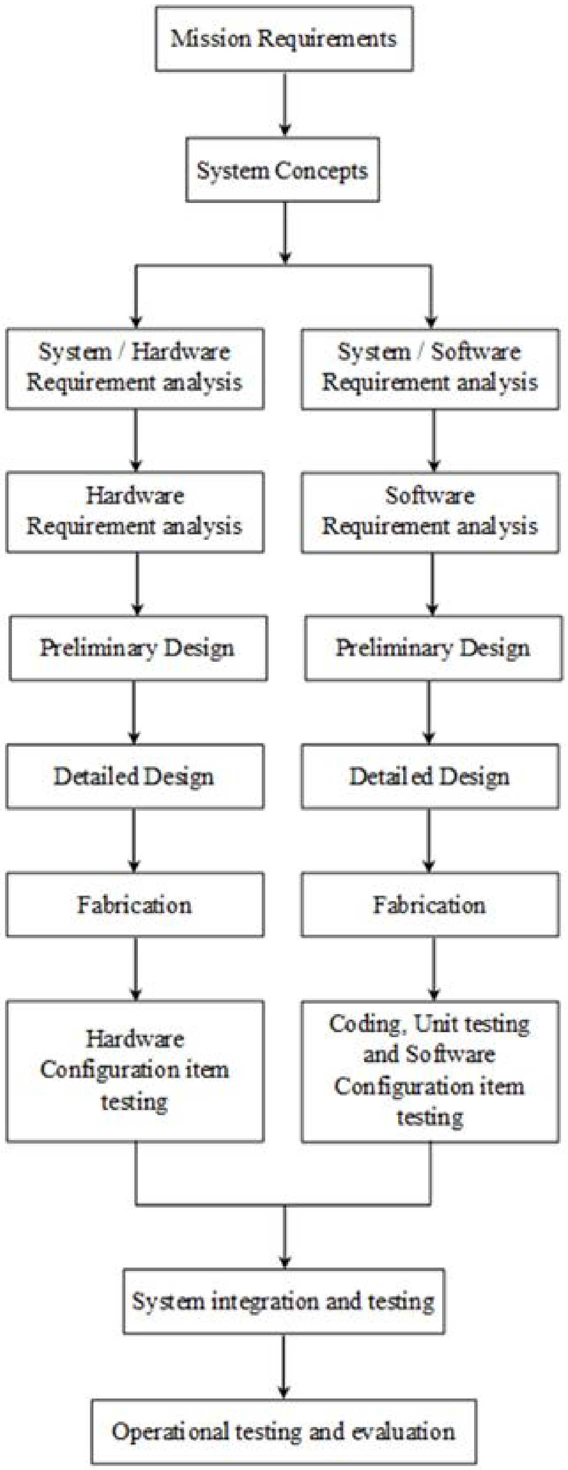

Figure 2: Typical overall system design approach

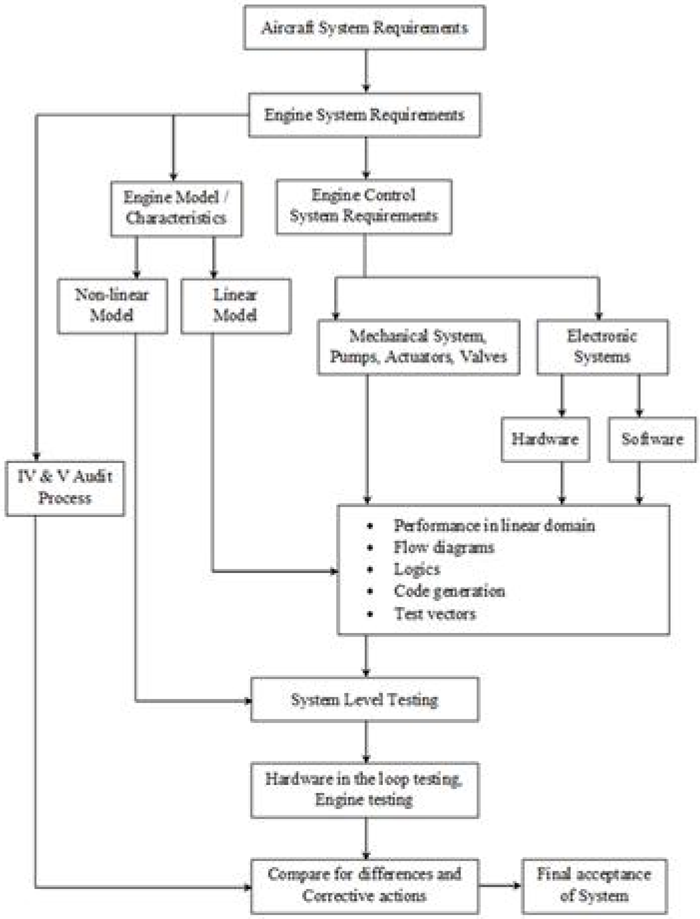

Figure 3: Typical approach for FADEC system design

4.1. The system requirements and audit process

In this approach capture of the requirements covering form, fit and functions was critical. Documentation and traceability at each stage from requirements to system level / sub-system level / component level was essential. The design process, the fabrication process, the assembly process, testing at unit level, sub-system and system levels had to be done in a methodical manner.

4.2. Independent verification and validation

The fundamental requirement was to show that the design of the configured system was verified and validated.

The design assumptions, the design philosophy, the configuration, the modeling and simulation work that encompassed the design had to be verified by an independent team to confirm the results obtained by the design team. After the design had been verified and accepted, there was a need to validate the design through appropriate experimental tests. This gave the proof that the design that had been conceived was able to demonstrate the performance and functionality requirements. The process of

Independent Verification and Validation that had been carried out gave the complete confidence to the customer that the system designed fully met the SOR.

5. Concluding remarks

The initial conceptualization of the GTX engine had given the challenging opportunities of configuring the control systems to operate the engine from start up to the maximum engine rotational speed. This had been essentially a bottom to top approach as there had been a concurrent process of capturing the engine requirements and developing the control system to the required level. This had been successfully carried out with mechanical control systems and subsequently with electronic systems. This then set the stage for setting a top to bottom approach for the next candidate engine when the system requirements were defined and frozen. The design, development and integration of the FADEC system with the engine system were then carried out in a formal manner. This successfully met the independent verification and validation requirements.

6. Acknowledgements

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