Real Time FPGA Simulation of an Aircraft Engine Model

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Abstract: In this paper, an aero-engine's thermo-dynamic models are built through complex differential equations that have to be solved iteratively in a stipulated time to predict engine dynamics accurately; an approach to simulate the model using an FPGA with an embedded processor is discussed. Dual core ARM processor ZC702 FPGA is is interfaced with an electronic controller through signal conditioners/ level shifters. The electronic controller feeds the model and the model in turn drives the feedback control system consisting of controller andan actuator.The sensor signals are simulated using Direct Digital Synthesis (DDS) technique. It is found that with 50 MHz clock source, it is possible to generate sinusoidal & TTL waveforms of upto 30 kHz using the on-board clock source.

Keywords: Aero-engine, engine control system, FPGA, real time simulation

1. Introduction

Engine Control System of an aero-engine schedules fuel flow, controls various geometries and ensures surge free operation such that the under both steady state and transient conditions, necessary thrust is delivered by the aero-engine to the aircraft.

Electronic Controller which is a part of the engine control system is equipped with embedded software where control laws execute and ensure the intended operation; the logics, schedules and gains are dependent on the mechanical control system and engine performance.

A realistic engine model in the early phase of controller design is vital to ensure compliance to system requirements; the controller has complex algorithms to ensure that dynamic performance of the aero-engine are met. A real time engine simulator is very vital to validate the electronic controller.This paper presents a methodology for simulating the engine model using a general purpose FPGA, in real time

2. Aero-Engineand Engine Control System- An overview

A typical twin-spool gas turbine engine consists of 2-3 fan stages, several high pressure compressor stages and2 turbine stages. The atmospheric air is compressed by more than 20 times by the fan andcompressorsanddelivered to the combustor. The pressurized fuel from a fuel system (fuel flow rate being proportional to the throttle command) is directed through burners after atomizing the fuel.

The fuel is ignited inside a combustor; the gas temperature and velocity shoot up. This high pressure, high temperature air is expanded in multiple turbine stages. A part of the energy is used to drive the compressor. The gases are further expanded in an exhaust nozzle and high velocity jet leaves the nozzle. The change in momentum of the air creates a forward force (thrust).

Most modern gas turbine engines have automatic control system to optimize the engine performance. The engine control system comprises of an actuator, an electronic engine controller fitted with feedback sensors and the plant (engine). Based on the pilot's throttle setting (thrust demand), the electronic controller commands the actuator of a fuel system to open an electro-hydraulic valve such that it meters an appropriate amount of fuel, to meet the thrust requirements.

3. Engine Model

Mechanical models of engine are developed using CATIA, SolidWorks etc.; these tools are useful in visualizing a systemandgenerally usedin manufacturing industry and to predict the mechanical aspects of a system.A thermo-dynamic model of a gas turbine engine captures the dynamic behaviour of the complete engine; these are built by studying the responses of the individual components of the engine and then collating all the data to build a complete engine model. The model can be continuously updated using test data collected from the field/ real world.

Gas turbine engine works on the basis of Brayton cycle; there are four thermodynamic processes- isentropic compression, isobaric combustion, isentropic expansion and heat rejection. As the gas moves through the engine, its temperature and pressure keep increasing and as the gas reaches the turbine stages, the pressures begin to fall. The altitude and speed at which the engine is functioning, the laminarity of the air inlet etc. make the aero-engine a very complex thermodynamic plant.

A typical engine model comprises of – the inlet stage, fan stage, high pressure compressor stage, combustor stage, low and high pressure turbine stages, the nozzle stage and after-burner stage.Complex mathematical equations of the third and fourth order characterize the performance of the engine very accurately. These capture the normal behavior of the engine and also enable failure mode worst case scenario studies.

4. Related Work

The research proposed in [1]discusses the implementation of an engine model on a mini-computer with 8192 memory words; this method implemented an engine model with first order differential equations.Implementation of fault data simulation in an aero-engine model using Simulink Matlab is discussed by Yi Geet al in their research proposed in [2]; elaborate explanation on the method to compute thermodynamic equations of engine model components and a method to introduce fault into those components is the crux of this paper; the equations corresponding to the compressor, combustor, different stages of turbine along with aerodynamic thermal calculations are discussed; faults such ascompressor surge, combustor flame-out, atomisation failure, ,nozzle thrust drop failure etc are explained and the means to simulate these faults are discussed

Implementation of engine model on an industrial computer is proposed in [3]; authors express difficulty in simulating some high resolution components of the engine model at small step sizes which lead the authors to adapt a multirate, multi-step size simulation using multiple processors.The importance of correctly modelling the dynamics of the fuel metering unit (in a non-HIL) testbench is discussed in [5]; the authors use process-based modelling and object-oriented modelling to enrich the component model of a turboshaft engine

The authors of Safran Helicopter Engines in [4]have proposed an invention wherein the electronic engine controller has an option to read its input data either from a real sensor or from a digital bus to which data is supplied from a real time simulation of the sensor; similarly the outputs can be directed at the physical actuator or onto a simulator; this arrangement is possibly used in on-board simulation of engine in a helicopter; this can be a future application of the current paper.

5. Simulation of the Model

The primary input of the engine model is the fuel flow. The atmospheric conditions in terms of altitude and speed of the aircraft are the secondary inputs. Based on these input conditions, the engine behavior is captured through the observable parameters such as the spool speeds, the temperature and pressures at the compressor and turbine stages.These parameters are also the basis for the operation of the electronic engine controller. In an engine scenario, the controller receives the engine parameters through sensors located on the engine (S1, S2…….S7) and generates the fuel flow requirement and gives an electrical signal (ActDrv) to the fuel system. An actuator in the fuel system delivers the necessary fuel flow; the actual fuel flow (WfAct) is measured indirectly through an LVDT sensor which in turn is sensed by the controller forming a feedback system.

In a model environment, the numerical values of the parameters equivalent to the engine (S1, S2……S7) parameters are generated by the model and these are conditioned to suit the input stages of the electronic controller signal conditioner stages.A model of the fuel system is also part of the simulation environment. This model generates the fuel flow parameter (WfActandLVAct) based on the electrical signal (ActDrv) of the electronic controller

A ZC 702 Evaluation Board is utilized to execute the mathematical model. This board with 512 MB DDR3 memory and 256 MB QSPI Flash is configured with Analog to Digital Converter (ADC)and UART peripherals. The board is also interfaced with Digital to Analog Converters (DAC) to generate the sensor signals. The functional block diagram depicting the same is shown in fig 1. An IP has been developed on the ZC702 FPGAfor generating the speed and pressure signal parameters.

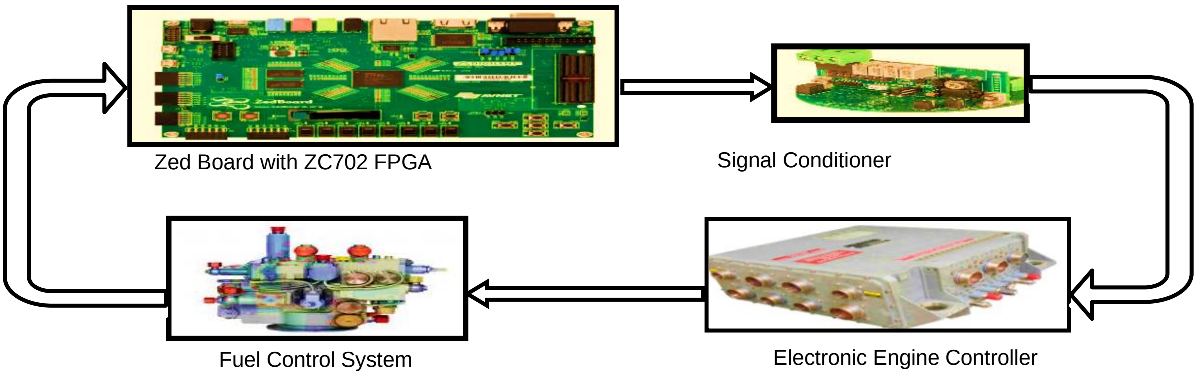

Figure 1 - Functional Block Diagram

The engine inlet conditions(Thrust, Altitude, and Aircraft Speed) are the primary inputs to the engine controller. The fuel system model generates the engine fuel flow(WfAct); the model executing on the FPGA processor simulates the sensor signals. These numerical values need to be converted to physical signals in order to feed the engine controller.

6. Simulation of Sensor Signals

The sensor used to generate the speed signal is a magnetic pulse probe; it senses the number of rotations of the engine spool. The signal waveshape is dependent on the shape of a gear tooth. The magnetic probe produces an electrical signal whose amplitude and frequency are a function of the engine spool speed.

Similarly the pressure is sensed using a pressure probe; the electrical signal is in the form of a TTL pulse whose frequency is proportional to the pressure.Sincethe controller has multiple sensors for redundancy purpose, upto 14 frequency signals are to be generated. Hence an IP is developed that can capture all the complex waveforms of the various sensors.

7. DDS Technique

DDS is a popular technique used to generate random waveforms in programmable function generators. Frequency can be quickly changed enabling frequency sweeps.

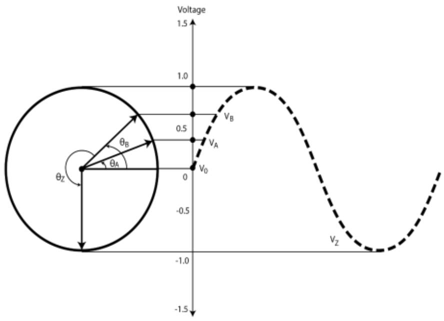

Figure 2–Amplitude and Phase relation of a sine wave

The relationship between the amplitude & the phase of a sine wave is explained in fig2. A template of the required waveform in terms of the amplitude values of a random waveform as a function of the waveform phase are stored in memory; by changing the rates at which the phase values are processed, the frequency can be quickly changed. The larger the number of phase points that are stored, better is the waveform definition.

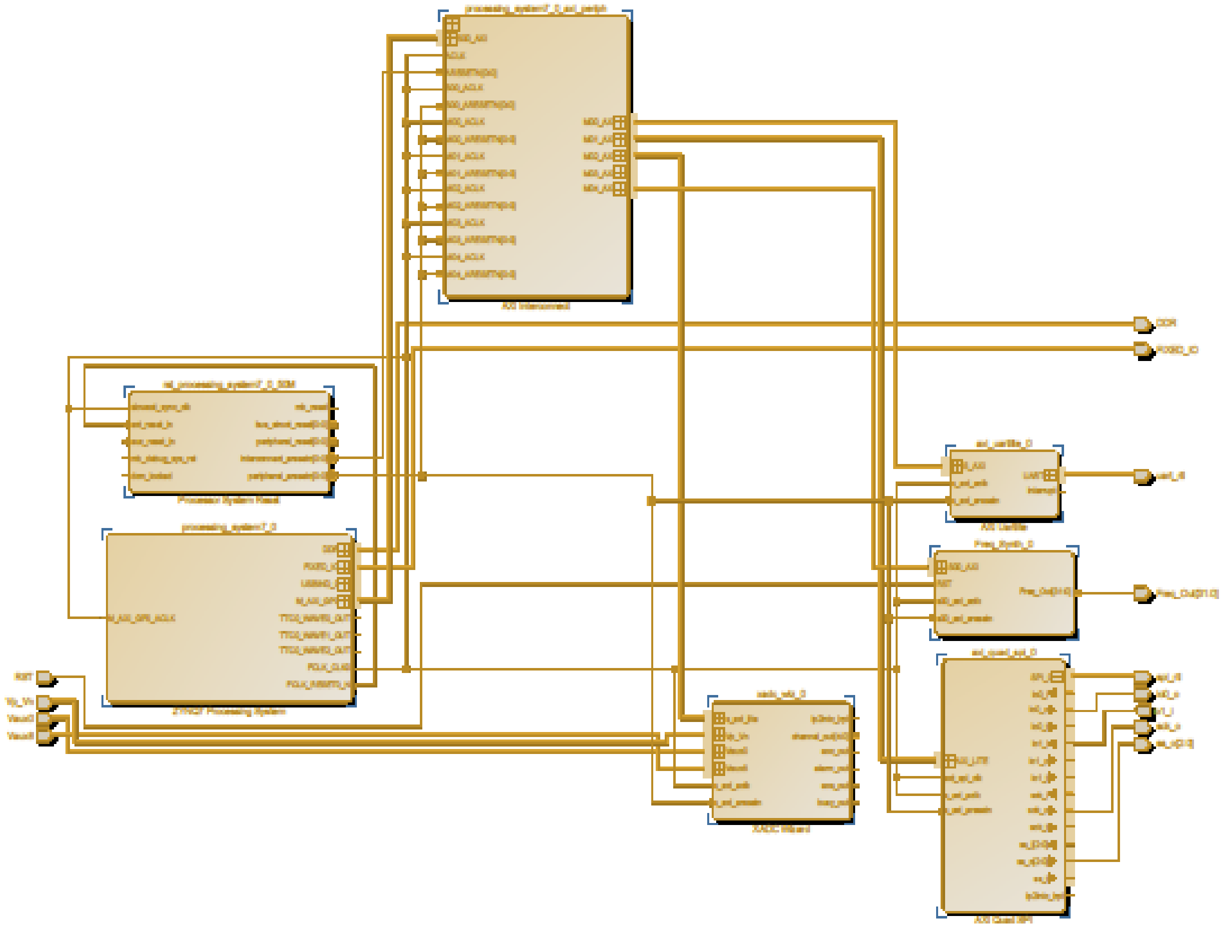

Figure 3 – Vivado IP for Frequency Synthesis

DDS logic is implemented in VHDL on the ZC702 board with 50 MHz Clock source and 27- bit counter as shown in fig 3 above.

8. Simulation Results and Conclusion

Generation of 500 Hz signal is simulated in the Vivado Test Bench as shown in fig 4. Sinusoidal and TTL waves from 100 Hz to 30 kHz are generated using the DDS technique. These signals are to be interfaces with the digital engine controller to study the closed loop dynamics of the engine. This will enable designer to fine tune the controller characteristics early in the design cycle

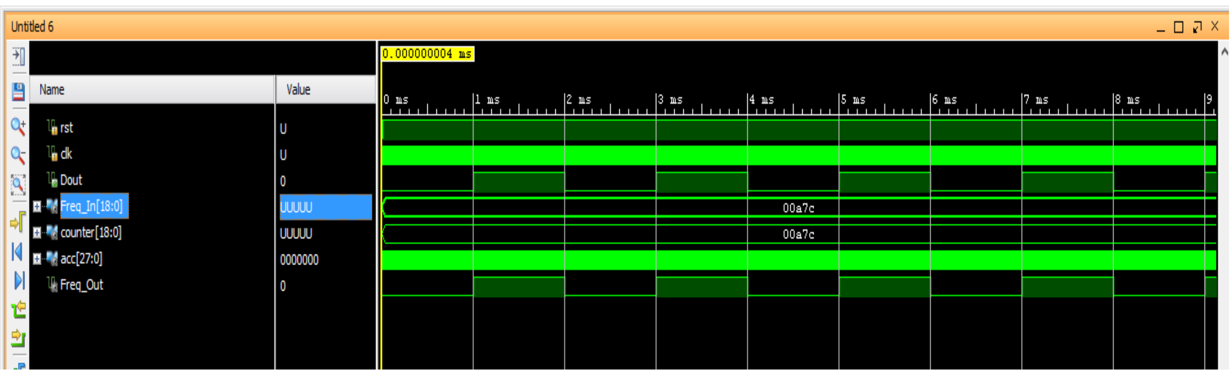

Figure 4 – Simulation Results

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