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Application of Analytical Techniques for Modeling and Simulation of Aircraft Engine Control System Sensors under Ideal Cycle Analysis Model

Md. Shaheriaz[1],
Phd Student, Dept. of EEE, BMS College of Engineering Bangalore,
Dr. Lakshminarayan C[2],
Professors and H.o.D Dept of EEE, BMS College of Engineering Bangalore,
Anitha K R[3]
M-Tech Student, Dept. of E&CE, BMS College of Engineering Bangalore,

ABSTRACT

Engine sensors data is crucial for control system. Sophistication in control system design needs reliable and uninterrupted data from engine. Physical sensors are exposed to high temperature and vibration environment inside the aircraft engine and are prone to damage. Any failure of engine sensors will affect the performance of control system. This paper presents a technique to simulate the sensors which exactly replicate the physical sensors. The sensors are modeled by analytical simulation and modeling technique, followed by extensive–verification and validation using aircraft flight envelope data present in design texts.

KEYWORDS/ABBREVIATIONS

T_t-Stagnation temperature(K), T_s -Static/thermodynamic temperature(K), u- Flow velocity (m/s), M- Mach number, R- Gas constant, T_0 - Absolute temperature(K),P_0 - Absolute pressure (Pa),T_a Temperature at sea level (288.16°k), P_a - Pressure at sea level (101.325kPa),h- Height or altitude(m), h_1 - Altitude at some point(m),g_0- Gravitational constant (9.81 m/s^2), ECS- Engine Control Systems, RTD- Resistance Temperature Detector

I INTRODUCTION

Analytical modeling uses a reference model of the engine and redundant information in dissimilar sensors to provide an estimate of a measured variable. Modeling is the imitation of the operation of a real world process or system over time.

It involves the generation of artificial history of a system, and the observation of that artificial history to draw inferences concerning the operation characteristics of the real system. In this work, both ideal cycles analysis and dynamic cycle analysis of aircraft turbofan engine is carried out and mathematical interrelations between different stages of the engine are developed. Thermodynamic relations are used to model the actual sensors with certain assumptions in software. For more details please refer **[1]** and **[2].**

II BASICS OF AERO ENGINES

Most aircraft engines work on the principle of taking a mass of air and accelerating it rearwards. This is inline with the Newton’s third law of motion which states” For every action, there is equal and opposite reaction”. By pushing air rearward, the reaction will cause the aircraft to move forwards. There are several ways of achieving the aircraft propulsion.

III INTRODUCTION TO ENGINE CONTROL SYSTEM

A simple engine control system computes the amount of fuel needed for the engine to produce a desired power (or thrust), based on pilot’s power request through a throttle or a power lever. An aircraft engine is designed to operate in a wide operating envelope (to support aircraft mission profiles). As shown in **figure1.**Typically, the altitude can vary from sea level to 50,000 ft (or even higher), the air speed can vary

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from Mach 0.8 for civil transport to beyond Mach 2 for supersonic fighters; furthermore, the air temperature at the same altitude and air speed can vary from a hot summer day to a cold winter night.

These ambient condition variations have imposed severe challenges on control system design for details refer **[3]** and **[4]**.

Gas turbine engine control system operating envelope

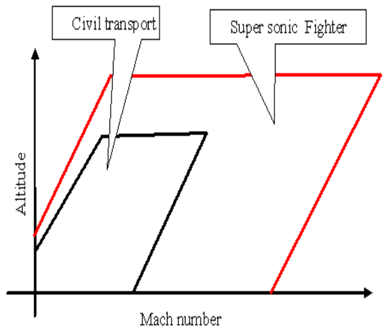

Figure 1: Gas turbine engine control system operating envelope.

IV ENGINE PARAMETERS

1. Thrust

Thrust is a mechanical **force**, which is generated through the **reaction** of accelerating a mass of gas, as explained by Newton's third law of motion. A gas or **working fluid** is accelerated to the rear and the engine and aircraft are accelerated in the opposite direction.

2. Pressure

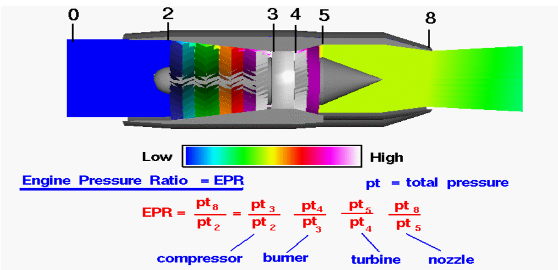

Figure2: Pressure variation in aircraft turbofan engine.

In **figure2** we can see how the flow pressure varies through a typical turbojet engine. The measure of pressure in different stages of engine is very essential for ECS design.

Pressure sensors are fixed in these sections to measure the pressure. Several types of pressure sensors are used to measure pressure. Most of ECS use vibration cylinder type of sensors for measuring engine pressure parameters.

3. Temperature

The temperature in aircraft engine increase as pressure increases since the compressor is doing work on the flow. In the burner a small amount of fuel is combined with the air and ignited at near constant pressure. The temperature of the flow reaches a maximum in the burner. Leaving the burner, the hot exhaust is passed through the turbine. The temperature sensors sense these temperature variations at different stages of the engine. RTDs and thermocouples are used to measure the engine temperatures for control purposes**[5].**

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V NEED FOR SENSORS MODELING

Since the aircraft engine sensors are subjected to a very high pressure, temperature and vibration, there are chances that sensors getting damaged. Any sudden and unexpected failure of sensors may completely degrade the performance of the engine control unit, even though engine and the control units are healthy. Also, under these conditions the monitoring of engine status will be difficult as some of key engine data will not be available. It is essential have a back-up for the engine sensors either by redundant sensors or virtual sensors. Additional sensors needs additional processing electronics, cables harnesses etc which adds to weight and cost. Hence virtual sensors are created by simulation by means of mathematical equations developed by splitting the aircraft engine into subsystems and interrelating these subsystems. These simulations can be enhanced to identify and isolate and replace the faulty sensor with virtual sensor. This ensures the reliability and availability of the system. In the present paper an attempt has been made to obtain simulated sensor outputs from engine thermodynamic relations with certain assumptions. Most of the calculations and simulations have been made with MATLAB**[6]**.

VI ENGINE CONTROL SENSORS

The engine being considered here is a low by pass, twin spool turbofan engine.

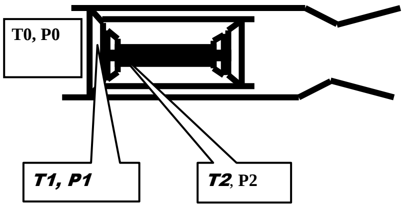

Figure 3: Different Sensors of control system.

The schematic diagram in figure3 shows various zones of engine control parameters simulated for the control system **Figure 3** shows location of few of the sensors which measure the engine parameters and used in control law of engine. The parameters of interest are indicted by highlighted nomenclatures. The current paper discusses analytical prediction of the control system sensor outputs.

VII ANALYTICAL MODELING OF SENSORS

1. Ideal Cycle Analysis

The thermodynamic behavior of airflow through an engine is studied in cycle analysis. Without regard for the mechanical means used to produce its motion. The engine components such as the inlet, the compressor and the turbine are characterized by the results they produce. The main application of cycle analysis is to determine which characteristics to choose for the various components of an engine to best satisfy a particular need **[7]**.

The characteristics of components determine the values of cycle analysis. In ideal cycle analysis all components are taken to be ideal and only conclusions insensitive to these assumptions are deduced. The following are the assumptions made,

1. The process of compression and expansion in the inlet, the compressor, the turbine, and the nozzle are isentropic (reversible adiabatic process).
2. The combustion in engine occurs at constant static pressure.
3. The working fluid is considered as a thermally perfect gas, with constant specific heat.
4. The exhaust nozzle expands the engine exhausts completely to ambient pressure

2. Stagnation temperature and pressure

The temperature reached when a steadily flowing fluid is stagnated (brought to rest) adiabatically, that is without transfer of heat to or from the fluid is called the stagnation temperature. The stagnation temperature is given by,

$$T_t = T\left(1+\frac{\gamma-1}{2}M^2\right) \quad \text{...(1)}$$

The stagnation pressure, P_t is defined as the pressure reached in the stream is brought to rest isentropically as well as adiabatically. Thus we have

$$P_t = P\left(1+\frac{\gamma-1}{2}M^2\right)^{\frac{\gamma}{(\gamma-1)}} \quad \text{...(2)}$$

The ratio of stagnation pressures across a component of the engine is denoted by 'π' with a subscript indicating the components ,'d' for diffuser, 'c' for compressor, 'b' for burner, 't' for turbine, and 'f ' for fan. The ratio of stagnation temperatures is denoted by 'τ'. The stagnation temperatures divided by ambient static temperature will be denoted by 'θ' with a subscript $\theta_0 = T_{t0}/T_0$

$$= \left(1+\frac{\gamma-1}{2}M_0^2\right) \quad \text{...(3)}$$

The stagnation pressures divided by ambient static pressures will be denoted by 'δ' so that

$$\delta_0 = P_{t0} / P_0 = \left(1+\frac{\gamma-1}{2}M_0^2\right)^{\frac{\gamma}{(\gamma-1)}} \quad \text{...(4)}$$

Thus $\delta_0 = \theta_0^{\frac{\gamma}{(\gamma-1)}}$ .... (5)

The stagnation pressure and temperature are the thermodynamic quantities in the situation where the Mach number is small at all the points in the engine at which the thermodynamic quantities are evaluated.

3 Cycle Analysis with Losses

The most important derivation from the ideal behavior described in ideal cycle analysis results from;

1. Imperfect diffusion of the free-stream flow from flight to engine inlet conditions.
2. Non isentropic compression and expansion in the compressor and turbine, incomplete combustion and stagnation pressure loss in the burners.
3. Variation of the gas properties through the engine due to temperature and composition changes.
4. Incomplete expansion (or over expansion) to ambient pressure in the nozzle.
5.

VIII SENSORS PARAMETERS COMPUTATION

The sensors are simulated based on the assumptions and results obtained from the cycle analysis as discussed above

1. Computation of T_0, P_0

The temperature T_0 and Pressure P_0 are stagnation/atmospheric quantities and can be computed by the help of pitotstatic tube. The analytical compotation is possible if the altitude information is available we can compute T_0 and P_0 as

$T_0=T_a+a(h-h_1)$. .... (6)

$$P_0 = P_a \times e^{-[g_0/(RT)](h-h_1)} \quad \text{.........(7)} \quad P_0 = P_a\left(\frac{T_0}{T_a}\right)^{-\frac{g_0}{(aR)}} \quad \text{.......................(8)}$$

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2 *Computation of T_1, P_1*

The forward speed has a significant effect on the intake section. Hence intake is considered as a separate component and not as a part of compression section. Intake is simply assumed as an adiabatic duct for a subsonic aircraft. Since there is no heat or work transfer, the stagnation temperature is constant although there will be a loss of stagnation pressure due to friction and due to shock waves at supersonic flight speeds. Under static conditions or at very low forward speeds the intake acts as a nozzle in which the air accelerates from zero velocity(C) or low C_a to C_1 at the compressor inlet. At normal forward speeds, however the intake performs as a diffuser with air decelerating from C_1 to C_a and the static pressure rising from P_a to P_1. The intake efficiency can be expressed in a variety of ways, but the two most commonly used are the isentropic efficiency η_i (defined in terms of temperature rise) and the ram efficiency η_r (defined in terms of pressure rise). η_i can be regarded as the fraction of the inlet dynamic temperature which is made available for isentropic compression in the intake. The intake temperatureT_1 and pressureP_1 can be found from

$$T_1 = T_0\left[1+\frac{\gamma-1}{2}M_0^2\right] \text{……………………..….(9)} \quad P_1 = P_0\left[1+\eta_i\frac{\gamma-1}{2}M_0^2\right]^{\frac{\gamma}{\gamma-1}} \text{……..(10)}$$

The ram efficiency can be shown to be almost identical in magnitude to the isentropic efficiency. Thus the two quantities are interchangeable. The intake efficiency will depend upon the location of the engine in the aircraft, for convenience η_i is assumed to be 0.93 relating to subsonic aircraft. It would be less than this for supersonic intake, the value decreases with increase in inlet Mach number. In practice, neither η_i nor η_r is used and it is more usual to quote value of stagnation pressure ratio as a function of Mach number only.

Hence $P_1 = P_0\left[1+\frac{\gamma-1}{2}M_0^2\right]^{\frac{\gamma}{\gamma-1}}$ ……………….. (11)

There are duplex sensors physically embedded in the engine inlet section to estimate T_1 and P_1. We can also compute T_1 and P_1 by using the values of the temperature T_0 and Pressure P_0 utilizing the isentropic relations mentioned above. Where T_1 = engine inlet temperature, P_1= engine inlet pressure, γ= 1.4 M_0= Mach number. Thus the information about altitude and Mach number is sufficient to compute the inlet values. The plots in **figure4 and 5** show the computed value of various inlet temperatures and pressures. More detailed explanation about the isentropic relations is present in reference **[7], [8] and [9].**

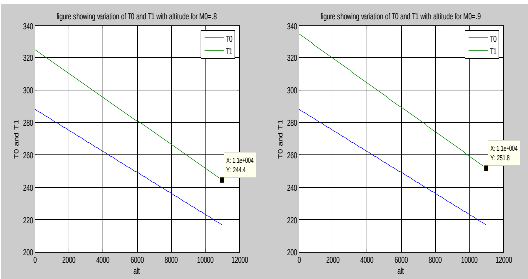

Figure4: showing variation of T0 &T1 with altitude for Mach number = 0.8 and 0.9.

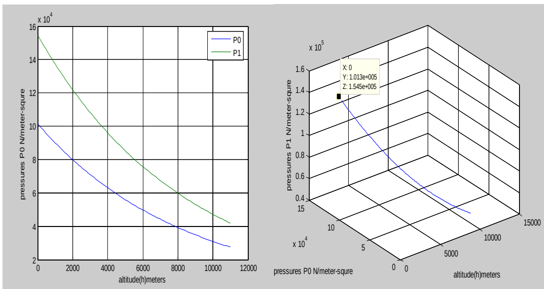

Figure5: Variations of P0 & P1 with respect to altitude, mach.8 number .

3. Computation of T_2

The compressor inlet temperature T_2 is computed by using the compressor characteristics. We know that losses in compressor originate primarily in regions of viscous shear on the blades and on the walls of the flow passage. These regions represent flow of lower stagnation pressure than the inviscid flow as in diffuser, at the compressor outlet there is an average stagnation pressure and an average stagnation temperature. Shock losses are also important in the fan stages and in the first stage of modern transonic compressors. For a given

stagnation pressure ratio, from inlet to outlet, the result of losses in a compressor is to require more energy input, than for an ideal compressor.

The efficiency is therefore defined as

$$\eta_c = \frac{\text{ideal work of compression for a given } \pi_c}{\text{Actual work of compression for a given } \pi_c} \quad \ldots\ldots\ldots\ldots(12)$$

Since the flow through the machine is practically adiabatic, the work of compression, all appears as stagnation temperature rise, and this definition is equivalent to

$$\eta_c = \frac{\pi_c^{(\gamma_c-1)/\gamma_c} - 1}{\tau_c - 1} \quad \ldots\ldots\ldots\ldots(13)$$

It must be noted that there are relationships between π_c and η_c. For compressors of different π_c, what is constant is the efficiency for a small pressure change and a corresponding small temperature change, this is termed as the "polytropic efficiency" denoted i.e. for a small P_t and T_t, Where P_t and T_t are stagnation temperature and pressure.

$$\eta_{pol} = \frac{(1+\Delta P_t/P_t)^{(\gamma-1)/\gamma} - 1}{1+\Delta T_t/T_t - 1} \quad \ldots\ldots\ldots\ldots(14)$$

Integrating the above equation and using in η_c equation we get

$$\eta_c = \frac{\pi_c^{(\gamma_c-1)/\gamma_c} - 1}{\pi_c^{(\gamma_c-1)/\gamma_c \eta_{pol}} - 1} \quad \ldots\ldots\ldots\ldots(15)$$

Thus by using these relations the fan efficiency can be computed if fan pressure ratio is known. The values of corrected rotational speed, mass flow rate, fan pressure ratio and efficiency are obtained from fan stand alone test data. The variation of mass flow, fan pressure ratio and efficiency with corrected rotational speed of the fan compressor is obtained.

A typical fan characteristic map with operating and surge line is shown in **figure 6**. Generally the fan operating line is fixed based on the available surge margin and maintained during engine operation by controlling fan rotor corrected speed.

Thus, we can obtain a relation between corrected fan speed and mass flow rate thorough the fan. From the fan stand alone tests data we can find pressure ration and efficiencies for corresponding corrected mass flow. Thus, Data of the fan rotor speed and engine inlet temperature and pressure primary data computing $P_{2,}$ $T_{2\cdot}$.

These values of compressor pressure ratio and the compressor efficiencies are used to compute the compressor temperature ratio given by

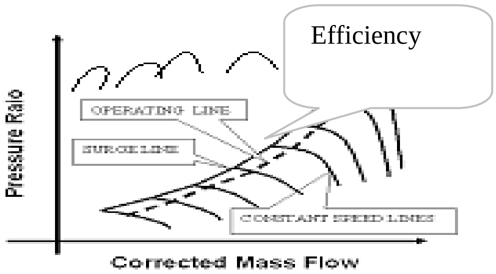

Figure6: A typical Fan characteristic map

$$\tau_c = \frac{\pi_c^{(\gamma_c-1)/\gamma_c}}{\eta_c} - \frac{(1-\eta_c)}{\eta_c} \quad \ldots\ldots(16)$$

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The value of compressor inlet temperature can be computed as

$$T_2 = \tau_c \times T_1 \text{..............................(17)}$$

IX RESULT AND DISCUSSION

In this work approach for sensors data modeling have been worked out. As mentioned earlier it is always ideal to have hardware redundancies in a system, however this additional hardware, manipulation software and the interfaces add to the system cost, weight. Analytical the approach discussed in this paper is a viable alternative to hardware redundancy.

For simplicity, only few sensors like T_1, P_1 and T_2 have been described in this paper. It is possible to extend the theory to all sensors on the engine. Essentially the modeling theory requires some other sensor data of upstream stations of an engine to predict the down stream data. Necessary sensor dynamic such as sensor lag, hysterasis, noise etc. needs to be inserted into the model.

CONCLUSION

The sensor model provides an alternative to the hardware sensors thus making the system more reliable. The simulated sensors can provide continuous engine data for both engine monitoring and for control system operation. It may be noted that computation of T_2 requires accurate characteristics of fan. It is always not possible to get fan characteristics in the entire flight envelope in an engine, which is still under development. Hence analytical models may be difficult to use to start with. However the modeled sensors can be refined during the engine developmental tests and can be used during service with high degree of confidence.

FUTURE WORK

Computation of T_2 requires accurate characteristics of compressor and fan. It is always not possible to get compressor and fan characteristics in an engine development program. Hence analytical models may be difficult to use. In the absence of design details of any system, system test data obtained during various tests can be used to generate empirical relations; an advanced approach of establishing empirical relations.

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