AIRCRAFT FUEL MASS ESTIMATION USING GLOBAL NONLINEAR PARAMETRIC MODELING

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Abstract

The accuracy of fuel measurement in aircraft tanks is directly related to flight safety and maneuverability. Capacitance gauging is widely used and is the industry accepted method for accurate measurement of the fuel quantity. In this paper, a global nonlinear parametric modeling technique is applied to estimate the fuel content using the capacitance probe data generated from 3-dimensional models of the aircraft fuel tanks. Automatic Net generation Tool for Structural Analysis (ANSA) software is used to create the fuel tank solid models. Using truth tables generated from ANSA software, several 3rd order polynomial models are developed. The fuel estimation algorithm is implemented in real time using Microcontroller based electronic unit.

Keywords: Fuel quantity, Fuel gauging probe, Automatic Net generation Tool for Structural Analysis (ANSA), Microcontroller, Time Processor Unit (TPU) channel

Introduction

Measurement of fuel mass in aircraft tanks is a challenging task. The accuracy of measurement is directly related to flight safety and maneuverability. The objective of fuel measurement system in aircraft is to gauge the fuel quantity in the tanks located in aircraft wings and fuselage. The distribution of fuel in individual tanks of the aircraft determines the location of center of gravity. Center of gravity plays a vital role in the stability analysis and design of flight control system, therefore, the wrong calculation of the same may affect the maneuverability of the aircraft. If the estimated fuel quantity is significantly higher than the actual fuel quantity available, then catastrophic consequences may occur due to lack of fuel in aircraft tanks to reach the destination. To overcome this, commercial aircraft often carry much more fuel than necessary to reach the destination. This additional fuel storage increases the total load on the aircraft.

Therefore, a reliable fuel gauging system is needed to operate the aircraft safely and efficiently. Measurement of fuel quantity in aircraft tanks is a complicated process. Since no sensor can directly measure the mass of liquid fuel, it is calculated from the fuel volume and fuel density. The fuel volume is calculated by determining height and orientation of the liquid surface in the fuel tanks. Ultrasonic or capacitance probes [1] can be used to determine the height and orientation of the liquid surface.

Further complications arise from complex geometric shapes of aircraft tanks, changes in orientation of the liquid
surface due to varying attitude, fuel sloshing due to aircraft accelerations, uncertainties in physical properties of the fuel due to atmospheric changes and different fuel blends. In the present method of fuel measurement, fuel volume is obtained by computing or experiment using output of probes that are installed in the aircraft fuel tanks along with flight attitudes pitch and roll. After that a look-up table (LUT) containing probes readings by fuel volume and flight status is built to store the data. During the flight, the fuel volume can be computed by interpolation based on the flight status, probe outputs and the look-up table. This analytical method requires large sets of data to be generated and stored, and it cannot handle complexities arising from irregular fuel tank shapes, fuel sloshing etc.

There are methods based on neural networks [2, 3] available in literature to compute the fuel content in aircraft tanks. Since the fuel estimation is a multi dimensional problem, the neural networks are well suited for this application. Radoslaw [2] used a Feed forward neural network with one hidden layer with sigmoidal neurons and a linear output neuron to estimate the fuel mass in aircraft tanks. Kai Hu et al. [4] formulated the fuel measurement as inverse problem and solved it with particle swarm optimization algorithm using neural networks to approximate input-output relationship of the process. Since neural networks are labeled as unpredictable by aviation community, the above methods are not suitable for flight safety-critical systems. In this paper, global nonlinear parametric models were developed to estimate the fuel quantity using the data generated from 3-dimentional models of aircraft fuel tanks. The model developed is combination of terms containing simple multiplications and additions of the flight parameters and therefore is suitable for real-time implementation.

The paper is organized as follows:

• Aircraft Fuel System Configuration describes the configuration of fuel system in aircraft.

• Global Nonlinear parametric Model Using Fuel Tank Model Data presents global nonlinear third order polynomial model developed using fuel tank model data.

• Real Time Fuel Content Estimation describes real time fuel content estimation using microcontroller based electronic unit.

• Simulation results are presented in section Results and Discussion.

• Finally some conclusions contains in section Conclusion.

Aircraft Fuel System Configuration

A typical schematic of aircraft fuel system is shown in Fig.1 with specific example of four fuel tanks: two wing tanks, a center tank located between two wings and a forward fuselage tank fore of center tank. The fuel system has been designed in such a way that fuel from wing tanks and forward fuselage tank are transferred to supply tank and from there it is pumped to the engine. The fuel transfer takes place through transfer valves located in the supply tank and are controlled by float valves. Initially both wing tanks simultaneously transfer fuel to the supply tank until the fuel content in the wing tanks is less than 100 kgs. After that forward fuselage tank starts transferring the fuel to the supply tank. Each tank is equipped with a set of capacitance probes to gauge the fuel quantity at any time. A total of 16 probes are installed in the tanks: 4 probes in each wing tank, 7 probes in supply tank, and one probe in forward fuselage tank. Some of the probes in each tank are equipped with built-in independent level switches to indicate the full and empty status. The level switches are electrically isolated from fuel content sensing circuit to avoid simultaneous failure.

Several methods of gauging fuel exist in the industry. The capacitance gauging is the most widely used and industry accepted method for accurate measurement. The basic principle of capacitance gauging is the difference in the dielectric properties of air and fuel. Capacitance probe consists of two concentric precision aluminum alloy tubes insulated from each other to form capacitance plates. The probe exhibits low capacitance when it is not immersed in fuel. As the fuel level varies, the length of the probe immersed in the fuel changes and the dielectric ratio of air to fuel changes and therefore the capacitance. This sensing capacitance is converted into frequency by an oscillator circuit. The capacitance can be calculated by using the Eq.1.

\[
C = C_0 + \frac{h}{L} (K - 1) C_0
\]

Where, \(C\) is the sensed capacitance, \(C_0\) is capacitance when probe is placed in air, \(h\) is the length of probe immersed in fuel, \(L\) is the length of the probe, and \(K\) is the dielectric constant.
Global Non-linear Parameteric Model Using Fuel Tank Model Data

In existing look up table (LUT) method, a look up table was generated through a fill and drain test on the aircraft tanks using a set of known quantities of fuel. For each case, the frequencies sensed by the probes that are mounted in the tank are tabulated. Look up table was generated only for the pitch attitude ranging from -3 deg to 3 deg with no change in roll attitude. The fuel quantity of a transferring fuel tank is computed based on the fuel flow rate data which is measure of fuel consumed by the engine.

Fuel gauging system is made redundant by computing fuel quantity based on fuel gauge probe signals and measuring the remaining fuel quantity by using fuel flow rate data. Redundancy for fuel gauging system is not available when fuel flow rate data alone is used for fuel quantity computation. Also fuel quantity measured using fuel flow rate data will be incorrect in case of fuel tank leakage. Hence an approach is required to be developed for fuel probe signals based fuel quantity computation which caters for various maneuvering conditions of fighter aircraft.

A technique is proposed based on global nonlinear modeling to estimate the fuel content by using the data generated from 3-dimentional models of aircraft fuel tanks. An important aspect of accurately modeling nonlinear functional dependence is determining the mathematical form relating independent variables to a dependent variable. In general, the goal is to find a compact model structure which still has adequate complexity to capture the nonlinearities. Models can be loosely classified as local or global. Local models are identified using data from a relatively small region of the independent variable space. A global model results when the range of validity for the identified model covers a large portion of the independent variable space.

This section gives the details of non-linear global model building from the truth tables. The truth tables generated from fuel tank model using ANSA simulation software contains fuel volume/mass at different fuel level, corresponding probe frequency and at different aircraft attitudes. The truth tables are generated for the pitch and roll variations from -45 degrees to 45 degrees.

Fuel tank model is developed by simulation of fuel tanks using ANSA software [12]. ANSA software slices the fuel tank model with gauging planes at different heights along the length of the fuel gauging probe considering the aircraft pitch and roll angles. By incrementally slicing the entire tank for each incremental change in pitch and roll angles, the tool generates a large database which defines all the relationships of fuel height to volume across all combinations of pitch and roll angles. Fuel tank model for fuel tank is shown in Fig.2.

CATIA is used to produce a solid model computer database of the fuel tank. This solid model database is based on the CAD drawings of the tank. Thus, the solid model database is defined by the geometric coordinates of the various surfaces and internal structures of the tank in terms of the local x,y,z coordinate system [8]. The solid model database is used as an input database to an analytical tool ANSA to build fuel tank analytical model. ANSA software is used to slice the fuel tank model with gauging planes at different heights along the length of the fuel gauging probe considering the aircraft pitch and roll angles. By incrementally slicing the entire tank for each incremental change in pitch and roll angles, a large database is generated which defines all the relationships of fuel height to volume across all combinations of pitch and roll angles [7].

Suppose ‘θ’, and ‘φ’ are the aircraft pitch and roll, the height to volume relationship can be derived from ANSA Fuel Tank Tool. The volume is a function of roll, pitch and height (Volume = f (θ, φ, h) [8]) where h is the fuel plane height above the origin of the arbitrary local coordinate system, φ is the roll data value and θ is the pitch data value. ANSA considers the immersed structure, components inside the fuel tank and displaces the liquid column accordingly.

The global nonlinear third order polynomial model developed for estimating fuel mass (M) using data generated from fuel tank model is shown in Eq.2.

\[
M = f (\theta, \phi, PF) = a_1 \times x_1^3 + a_2 \times x_2 \times x_3^2 + a_3 \times x_2^2 \times x_3 + a_4 \times x_2^3 + a_5 \times x_1 \times x_2^2 + a_6 \times x_1 \times x_2 \times x_3 + a_7 \times x_1 \times x_2^2 + a_8 \times x_1 \times x_3 + a_9 \times x_1^2 \times x_2 + a_10 \times x_1^3 + a_11 \times x_2^2 + a_12 \times x_2 \times x_3 + a_13 \times x_2^2 + a_14 \times x_1 \times x_3 + a_15 \times x_1 \times x_2 + a_16 \times x_1 \times x_3 + a_17 \times x_3 + a_18 \times x_2 + a_19 \times x_1 + a_20;
\]

(2)

where, a1, a2, ..... a20 are the coefficients

\[
x_1 = (b_1 - \phi) / s_1;
\]

\[
x_2 = (b_2 - PF) / s_2;
\]

\[
x_3 = (b_3 - \theta) / s_3;
\]
b1, b2, b3 are bias values for $\phi$, PF, $\theta$ respectively
s1, s2, s3 are scaling factors for $\phi$, PF, $\theta$ respectively
$\phi$, $\theta$ are pitch and roll angles in radians respectively
PF is the probe time period in $\mu$ sec

Coefficients are estimated using the least squares method [9]:
$$C = (P^T P)^{-1} P^T Y$$

Real Time Fuel Content Estimation

Fuel content measurement in real time is estimated using Microcontroller based Electronic unit. Electronic unit acquires the fuel gauge probe signal using Microcontroller’s Time Processor Unit (TPU) channel [10]. It is a 32 bit Micro controller running at 16 MHZ clock speed. It has 16 independent TPU channels and two timer counters. TPU channel is configured in Programmable Time Accumulator (PTA) mode [11].

The fuel gauge probe signal is measured by TPU channel for a specified number of periods. After the elapse of specified number of periods, TPU updates the result in terms of 32-bit count. An interrupt signal is generated to the Microcontroller and the measurement process is restarted. Each 32-bit count corresponds to 250ns period by selecting the Timer counter 1 (250ns period) as the time base for the TPU channel [11].

Moving average of eight samples of the acquired fuel gauge probe signal is done by the Electronic unit in order to filter out the noise. The fuel gauge probe signal is validated by checking for its range. If the signal is found to be out of its range for more than the specified persistence time, it will not be used for fuel quantity estimation.

The computation is done for every 80 milliseconds in a continuous loop. The fuel quantity is gauged from the estimated coefficients, fuel gauge probe data, pitch angles and roll angles when the probe signal is in the gauging zone i.e within Twet and Tdry limits as shown in Fig.3. Twet and Tdry limits correspond to the fuel gauge probe frequency signals when the probe is fully immersed and fully dry. The fully immersed and dry condition of the probe indicates the fuel tank capacity as full or empty. The estimated coefficients are used to gauge the fuel quantity as shown in Eq.3 when the fuel gauge probe is in the gauging zone. When the fuel probe is in gauging zone and not failed, the above equation is used to estimate the fuel quantity for each probe. The average of the fuel quantity estimated for the probes is computed to gauge the fuel quantity of a fuel tank.

Fuel content is computed using the following equation when the fuel probe is in gauging zone:

$$Y = a_1 x_3^3 + a_2 x_2 x_3^2 + a_3 x_2^2 x_3 + a_4 x_2^3 + a_5 x_1 x_3^2 + a_6 x_1 x_2 x_3 + a_7 x_1 x_2^2 + a_8 x_1 x_2 x_3 + a_9 x_1^2 x_2 + a_{10} x_1^3 + a_{11} x_3^2 + a_{12} x_2 x_3 + a_{13} x_2^2 + a_{14} x_1 x_3 + a_{15} x_1 x_2 + a_{16} x_1^2 + a_{17} x_3 + a_{18} x_2 + a_{19} x_1 + a_{20}$$

where, $a_1, a_2, \ldots, a_{20}$ are the coefficients

$$x_1 = (b_1 - \Phi) / s_1$$
$$x_2 = (b_2 - PF) / s_2$$
$$x_3 = (b_3 - \theta) / s_3$$

where $b_1, b_2, b_3$ are bias values for $\Phi$, PF, $\theta$ respectively
$s_1, s_2, s_3$ are scaling factors for $\Phi$, PF, $\theta$ respectively.

Results and Discussion

The results of mathematical third order polynomial model using PC based simulator are shown in Fig.4 and Fig.5 for various pitch and roll angles. It is found that the fuel quantity estimated (est) using mathematical third order polynomial model is matching well closer to the fuel quantity (true) in the truth tables which are generated by using fuel tank model. Mathematical third order polynomial model fit is found to be more accurate.

Real time implementation in electronic unit based on mathematical model is tested at Test Rig which has dynamic flight test environment facility. The results of the real time implementation of fuel quantity estimation using third order polynomial model (ANSA) is verified with the actual aircraft data (LUT) for FT2, LHWT and RHWT tanks respectively as shown in Fig.6, 7 and 8. The results indicate that the estimation is more consistent and accurate. There was an offset of around 40 Kgs found due to the fuel quantity which is ungaugeable with the actual fuel tank in the aircraft whereas in case of fuel tank model using ANSA it can be computed. Fluctuations were found to be smoothened with ANSA based mathematical model and the results are more accurate.

Conclusion

A global nonlinear 3rd order polynomial model has been developed to estimate the fuel quantity using the data estimated for the probes is computed to gauge the fuel quantity of a fuel tank.
generated from 3-dimentional models of aircraft fuel tanks. A real time computational model based on fuel tank model method is developed successfully. It can be used for modeling any irregular shape of fuel tank and it is practically demonstrated that the fuel quantity estimated by this method matches well with the actual aircraft data.

An onboard program was developed using Microcontroller based Electronic unit and tested at test rig which has dynamic flight test environment facility. The results obtained are found to be more accurate and reliable. The real time computational model onboard program can be improved further by catering for all the dynamic flight conditions of aircraft for better accuracy of fuel quantity estimate.

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References


Fig.1 Schematic of Aircraft Fuel System
Fig. 2 Fuel Tank Model of FT2 Fuel Tank

Fig. 3 Real Time Implementation Using Mathematical Model

Fig. 4 Fuel Quantity Estimation Using Third Order Polynomial Model of Wing Tank Fuel Probe for 30 deg Pitch and Various Roll Angles
Fig. 5 Fuel Quantity Estimation Using Third Order Polynomial Model of Wing Tank Fuel Probe for -30 deg Pitch and Various Roll Angles

Fig. 6 Real Time Fuel Quantity Estimation of FT2 Using Third Order Polynomial Model

Fig. 7 Real Time Fuel Quantity Estimation of LHWT Using Third Order Polynomial Model

Fig. 8 Real Time Fuel Quantity Estimation of RHWT Using Third Order Polynomial Model