TECHNICAL NOTE

AIRCRAFT FUEL ESTIMATION BY LEAST SQUARE TECHNIQUE

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Abstract

A least square estimation technique has been proposed for in-flight fuel estimation for a high performance combat aircraft. This paper presents the details of least square models for aircraft fuel estimation, the procedure for building the least square models and their fidelity to estimate the fuel quantity in the multiple internal fuel tanks of the aircraft from flight data. The performance of the fuel estimation by least square technique has been verified with 56 different post flight data with different maneuvers including probe failure cases and compared with lookup table based estimates, the technique currently being used on the aircraft. Few results of fuel quantity estimates are presented and discussed. Sensitivity of the least square model based fuel estimation technique to probe failures has been studied by simulating multiple probe failures in flight data.

Keywords: *Aircraft fuel estimation, Capacitance probes, Least Square techniques*

Nomenclature

DTOT = De-totalizer (used as reference to indicate total fuel content in the aircraft tanks)
LHWT = Left hand wing tank
RHWT = Right hand wing tank
F1A = Forward fuselage tank
F1/F2 = Fuselage supply tank
LUT = Look Up Table
FCG = Fuel capacitance gauging
LS = Least Square
y = Fuel content in a particular tank
c = Estimated Least Square coefficients
A = Matrix of measurements recorded during flight
N = No. of measured data points used for LS coefficient estimation
J_x = Aircraft forward accelerations in m/s^2
J_z = Aircraft normal accelerations in m/s^2
ϕ = Aircraft roll attitude
θ = Aircraft pitch attitude

Introduction

In-flight measurement of fuel content in each of the multiple fuel tanks of an aircraft is a complicated process. First and foremost is the observation that no sensor can directly measure mass of liquid fuel. The liquid mass must be calculated based on the measurement of parameters that are related to mass, such as the liquid volume and then either measuring or assuming density for the liquid fuel. Known liquid gauging systems typically gauge liquid volume by attempting to determine the height and orientation of the liquid surface in the container. Once the liquid plane surface is defined and located, the information can be converted to a volume and then equivalent mass. Such systems typically use liquid height sensors such as cylindrical capacitance sensors [1,2] or ultrasonic sensors [3] or optical pressure sensors [4] to determine the height of the liquid in the container. In aircraft fuel gauging, the process is complicated by numerous factors, including aircraft dynamic maneuvers, acceleration effects, fuel density changes due to temperature and pressure variations from altitude and atmospheric changes, different fuel blends, etc. Therefore, aircraft fuel gauging is necessarily a dynamic process during flight. To solve such dynamic problem, techniques like multi sensor data fusion [5], neural networks [6,7] and optimization algorithms [8] have been used. The problems associated with fuel gauging are further compounded by the fact that aircraft fuel tanks generally have complicated geometrical shapes and typically include number of internal structures. Hence fuel

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Paper Code : V66 N3/845-2014. Manuscript received on 29 Nov 2013. Reviewed, revised and accepted as a Technical Note on 10 Jun 2014

probes are placed or mounted at optimal positions within the fuel tank to accurately determine the fuel quantity [9].

The aircraft under discussion is equipped with four internal fuel tanks: two fuselage tanks (F1A and F1/F2) and two wing tanks (LHWT and RHWT). Aircraft fuel system has been designed in such a way that fuel from LHWT, RHWT and F1A tank are transferred to supply tank F1/F2 from there it is pumped to the engine as shown in Fig.1.

There are total 16 Fuel Capacitance Gauging (FCG) probes distributed in four fuel tanks as shown in Table-1 for fuel content gauging.

The fuel content in the internal tanks of the aircraft are currently being estimated based on Look Up Table (LUT) which relates the probe output to the fuel content. Current LUT based in-flight fuel estimation scheme indicates sudden increase in contents during certain flight regimes due to movement of fuel within the tank and gauging process switching from one probe to another. To overcome this problem a simple data driven procedure based on Least Squares (LS) model fit [10-12] to estimate LS coefficients which relate the probe output, aircraft accelerations and aircraft attitudes to fuel content in the individual tanks using post flight data is conceptualized, implemented and verified. This method shows promise in terms of improvement of the fuel content estimation compared to the existing LUT method.

Table-1 : Aircraft Fuel Tanks and FCG Probes

Fuel Tank	Probe Name
F1A (Fuselage Tank)	F1A_B (Bottom mounted)
LHWT (Left Hand Wing Tank)	LH_FT (Forward top mounted) LH_OT (Outward top mounted) LH_AI (Aft immersed) LH_FI (Forward immersed)
RHWT (Right Hand Wing Tank)	RH_FT (Forward top mounted) RH_OT (Outward top mounted) RH_AI (Aft immersed) RH_FI (Forward immersed)
F1/F2 (Fuselage Tank also called Supply Tank)	F1_FB (Forward bottom mounted of F1) F1_FT (Forward top mounted of F1) F2_FT (Forward top mounted of F2) F2_FB (Forward bottom mounted of F2) F2_AT (Aft top mounted of F2) F2_AB (Aft bottom mounted of F2)

This paper presents the details of LS models for aircraft fuel estimation, the procedure for estimating the LS models and their fidelity to estimate the fuel quantity in the internal fuel tanks from flight data. The performance of the LS models in fuel content estimation has been verified with data from 56 different flights and compared with corresponding LUT estimates. Few results of fuel quantity estimation by LS models from flight data (with and without probe failure cases) are presented and discussed. Sensitivity of the LS models to probe failures has also been studied by simulating multiple probe failures in flight data.

In Section - Lookup Table Method presents the in-flight fuel estimation method currently employed on the aircraft using Lookup Tables. In Section - Least Square Method gives the details of proposed LS model based aircraft fuel estimation, the procedure for building the LS models and estimating the fuel quantity in the individual fuel tanks using estimated LS models and few results with sensitivity studies. The concluding remarks are presented in the Conclusion Section.

Lookup Table Method

Look Up Table (LUT) which relates the probes output to the fuel content in the tanks is generated experimentally through fill and drain test on the aircraft in a fuel test rig using measured quantities of fuel. The experiment is carried out with aircraft at 3 deg pitch up. A known quantity of fuel is drained out from each of the tanks and the output of the probes that are mounted in the tank are recorded and tabulated against the fuel quantity present in the tank.

Problems Observed with the LUT Method

Due to limitations in the experimental setup at the fuel test rig, the LUT generated from the fill and drain test is valid only for the pitch attitude ranging from -3° to 3° with zero roll attitude. During the flight, the fuel content in the tanks is computed by interpolation based on the, aircraft attitudes and accelerations, probe outputs and the look-up table. For fuel pitch attitudes between 15° nose-up and -7° nose-down the contents are computed based on FCG probes output through lookup table. For pitch attitudes greater than 15° nose-up and less than -7° nose-down the contents in the tanks are computed based on fuel flow rate (using reading from fuel flow meter which is connected between supply tank F1/F2 and engine). During flight, fuel pitch attitude is deduced from $-\tan^{-1}(J_x / J_z)$, where J_x is the forward aircraft body acceleration and J_z the normal aircraft body acceleration. With this arrangements following problems were observed during in-flight estimation of fuel contents in the tanks.

Often sudden increase in content is observed during flight which is suspected to be due to:

- Movement of volume of fuel to locations, where higher contents will be gauged, in certain flying conditions.
- Gauging process switching randomly from one probe to another within the same tank.

Compensation or correction to the fuel contents is not accounted for attitude beyond ± 3°.

Figure 2 shows estimated fuel content from LUT method from one of the flights. It also shows the aircraft attitudes recorded during flight. DTOT (de-totalizer) is the reference value of the total fuel content from all fuel tanks and this is computed from the fuel flow meter which is connected between supply tank F1/F2 and the engine. It can be observed that the total fuel content of the aircraft from LUT estimate is not matching well with the DTOT reference when the aircraft is maneuvering. This is expected since the LUT is valid only for the pitch attitude between ± 3°.

Least Square Method

Since huge amount of flight test data of the aircraft is available, a mathematical model for estimating the fuel contents using a "data driven" approach is evolved. The idea is to arrive at a simple mathematical model relating the measured fuel probe readings, aircraft accelerations and attitudes to the fuel content in the tank. Inclusion of aircraft accelerations and attitudes into the model is expected to give mathematical model the capability to estimate the fuel content in the tanks more accurately under all maneuvering conditions.

Initially a set of LS coefficients has been estimated separately for each of the 16 FCG probes using recorded time histories of individual probe data, aircraft accelerations, aircraft attitudes from the same flight(s) as input and the fuel content (of the tank in which the particular probe is located) time history as output. Once the LS model coefficients are estimated, fuel content in the tanks is computed in real time by multiplying the estimated LS coefficients with FCG probe output, aircraft acceleration and aircraft attitudes. Fig.3 shows the block diagram of LS method for aircraft fuel estimation.

Least Square Models

For LS coefficient estimation, the fuel gauging system is modeled as:

$$y = A * c + \eta \tag{1}$$

where

y : vector of fuel content measurements in a tank (Kgs).
A : matrix of FCG probe, aircraft forward and vertical accelerations and aircraft roll and pitch measurements.
c : vector of unknown LS coefficients.
η : measurement noise which is assusmed to be zero mean, white, gaussian.

For example,

$$\begin{bmatrix} y \\ . \\ . \\ . \\ . \end{bmatrix}_{Nx1} = \begin{bmatrix} 1 & Probe & J_x & J_z & \phi & \theta \\ . & . & . & . & . & . \\ . & . & . & . & . & . \\ . & . & . & . & . & . \\ . & . & . & . & . & . \end{bmatrix}_{Nx6} \begin{bmatrix} c_1 \\ c_2 \\ c_3 \\ c_4 \\ c_5 \\ c_6 \end{bmatrix}_{6x1} + \eta$$

Where

$Probe$: FCG probe measurement (μ sec),
J_x : measured aircraft forward acceleration (m/s^2),
J_z : measured aircraft vertical acceleration (m/s^2),
ϕ : measured aircraft roll (deg)
θ : measured aircraft pitch (deg)
$c_1, c_2, c_3, c_4, c_5, c_6$: vector of unknown LS coefficients
N : Number of measurement data

Then the unknown coefficients corresponding to each probe are estimated in least square error sense as

$$\hat{c} = (A^T A)^{-1} A^T y \tag{2}$$

The LS coefficients are estimated with the data only when the probe output is within the valid limits (that is when the particular probe is in gauging) and then subjected to spike removal and noise filtering. Since there are 16 probes in the fuel gauging system, it requires 16 separate models to estimate 16 sets with 6 coefficients in each set.

For example, LS coefficients for LH-FT Probe in LHWT are estimated from the following equation:

$$\begin{bmatrix} c_1 \\ c_2 \\ c_3 \\ c_4 \\ c_5 \\ c_6 \end{bmatrix}_{6x1} = \left[\begin{bmatrix} 1 & . & . & . & . \\ LH\_FT & . & . & . & . \\ J_x & . & . & . & . \\ J_z & . & . & . & . \\ \phi & . & . & . & . \\ \theta & . & . & . & . \end{bmatrix}_{6xN} \begin{bmatrix} 1 & LH\_FT & J_x & J_z & \phi & \theta \\ . & . & . & . & . & . \\ . & . & . & . & . & . \\ . & . & . & . & . & . \\ . & . & . & . & . & . \end{bmatrix}_{Nx6} \right]^{-1} \begin{bmatrix} 1 & . & . & . & . \\ LH\_FT & . & . & . & . \\ J_x & . & . & . & . \\ J_z & . & . & . & . \\ \phi & . & . & . & . \\ \theta & . & . & . & . \end{bmatrix}_{6\,xN} \begin{bmatrix} y_{LH} \\ . \\ . \\ . \\ . \end{bmatrix}_{N\,x1} \quad (3)$$

Where

LH_FT : LH_FT probe output in m sec

y_{LH} : fuel content measurement in LH wing tank

Reconstruction of Fuel Content Time History

From the Eqn.(3) it can be seen that to estimate LS coefficients, the time histories of individual probe measurement, aircraft accelerations, aircraft attitudes and the fuel content (of the tank in which the particular probe is located) from the same flight are required as input. Since the accurate or directly measured time history of fuel content for each of the aircraft fuel tanks is not available from the flight data, for the purpose of estimating the LS coefficients the fuel content time history is reconstructed using (i) fuel content estimated from LUT during flight when aircraft roll attitude ϕ is $5° > \phi > -5°$, aircraft pitch attitude θ is $5° > \phi > -5°$, aircraft forward acceleration Jx is $5m/s^2 > Jx > -5m/s^2$ and aircraft vertical acceleration Jz is $-4.8m/s^2 > Jz > -14.8m/s^2$ during the flight and (ii) flow meter output during other periods of the flight. This reconstructed fuel content output is further filtered to obtain a smooth trajectory. After reconstruction of fuel content trajectory for each fuel tank, they are added up and compared with DTOT reference to ensure the consistency and accuracy of the reconstructed fuel content trajectory for each individual tank. The reconstructed fuel content trajectory is assumed to be more accurate than the LUT estimate because the latter has large unexplainable fluctuations and the LUT itself is valid for only 0 to 3 deg pitch attitude. Fig.4 shows the reconstructed fuel content trajectory for one of the tanks.

Estimation of Least Square Models

For LS coefficients estimation, the flight data (probes output, Jx, Jz, ϕ and θ) and reconstructed fuel content trajectories from 15 different flights are concatenated end to end as one set of data. From this concatenated data, sets of 6 LS coefficients have been estimated separately for each of the 16 FCG probes using noise filtered individual probe data, Jx, Jz, ϕ and θ time history and the reconstructed fuel content (of the tank in which the particular probe is located) time history using Eqn. (3). The estimated LS coefficients corresponding to each individual FCG probe are given in the Tables-2 to 5 along with their standard deviations.

The fuselage tank F1/F2 has seven fuel probes, three top mounted (F1FT, F2FT and F2AT) and four bottom mounted (F1FB, F1AB, F2FB and F2AB). The bottom mounted four probes are not modeled as sufficient data is not available from any of the flights available. This is because these probes comes into gauging only when the total fuel on the aircraft is less than 450 Kgs and the aircraft generally will be landed before the aircraft fuel content reaches this level.

Table-2 : Estimated LS Coefficients for LH Wing Tank

	FT Probe		OT Probe		AI Probe		FI Probe	
	Coeff	Std	Coeff	Std	Coeff	Std	Coeff	Std
c_1	-187.2281	± 2.2619	-57.0214	± 4.2817	-425.6955	± 1.4693	495.3852	± 15.3437
c_2	4.1359	± 0.0164	2.2193	± 0.0322	3.9486	± 0.0114	0.6705	± 0.0061
c_3	14.3743	± 0.1763	8.3132	± 0.2948	-10.6565	± 0.1875	6.2074	± 0.4460
c_4	1.8882	± 0.0560	0.6664	± 0.0663	-0.1247	± 0.0399	4.6661	± 1.5648
c_5	-0.1896	± 0.0074	-0.0121	± 0.0083	-0.2504	± 0.0060	9.7022	± 0.1559
c_6	0.5020	± 0.0391	0.7059	± 0.0414	1.1145	± 0.0326	5.2964	± 0.0968

Table-3 : Estimated LS Coefficients for RH Wing Tank

	FT Probe		OT Probe		AI Probe		FI Probe	
	Coeff	Std	Coeff	Std	Coeff	Std	Coeff	Std
c_1	-178.6709	± 3.0982	-92.1465	± 5.4962	-572.2018	± 1.0854	436.4503	± 5.6900
c_2	4.0284	± 0.0225	2.6631	± 0.0421	5.1998	± 0.0085	1.2971	± 0.0020
c_3	31.8740	± 0.2756	-1.2793	± 0.3798	1.3477	± 0.1301	9.6812	± 0.1423
c_4	3.2319	± 0.0774	-1.3930	± 0.0883	-0.2843	± 0.0299	4.8800	± 0.5796
c_5	-0.0070	± 0.0098	0.0033	± 0.0110	0.0219	± 0.0043	2.5414	± 0.0500
c_6	1.2037	± 0.0496	0.0576	± 0.0741	0.1262	± 0.0188	-2.0492	± 0.0333

Table-4 : Estimated LS Coefficients for F1A Tank

	F1A_B Probe	
	Coeff	Std
c_1	-538.5089	± 0.6793
c_2	5.2781	± 0.0045
c_3	21.3915	± 0.0920
c_4	3.5215	± 0.0236
c_5	0.0178	± 0.0035
c_6	0.0671	± 0.0150

Fuel Content Estimation by Least Square Model

Once LS coefficients are estimated for all the fuel probes, the fuel quantity in the fuel tank is estimated in flight by simply multiplying the probe outputs, J_x, J_z, ϕ, θ with the corresponding estimated LS coefficients as shown in Eqn.(1) at each data sample and then fuel quantity in the tank is arrived at by taking the average from all the probe under gauging in that particular tank. The fuel quantity is estimated from estimated LS coefficients only when the probe is within its gauging limits. If the particular probe in the tank is out of gauging or failed, it will be excluded from the computation of fuel quantity. Further, estimated fuel quantity of each tank is subjected to other logics based on information on maximum fuel rate from each tank, FULL/EMPTY switch status, probe/switch threshold values, etc. to improve the accuracy/robustness of the fuel estimates (the details of these logics were not given here because of restrictions).

Least Square Models Verification and Validation

The performance of LS models in estimating fuel content has been verified with 56 different post flight data. Fig.5 and 6 shows the comparison of fuel quantity estimation by LS models and LUT method from two different post flight data including probe failure case.

Table-5 : Estimated LS Coefficients for F1/2 Tank

	F1Ft Probe		F2FT Probe		F2AT Probe		F1FB, F1AB F2FB, F2AB
	Coeff	Std	Coeff	Std	Coeff	Std	
c_1	231.3557	± 1.3076	536.5468	± 0.6853	473.5603	± 0.7178	Not Modeled as they were not under gauging during flight.
c_2	3.3495	± 0.0092	1.2915	± 0.0051	1.7428	± 0.0049	
c_3	26.1876	± 0.1002	-3.8869	± 0.0519	-19.8848	± 0.1251	
c_4	3.7826	± 0.0212	0.3910	± 0.0143	0.2875	± 0.0244	
c_5	-0.0131	± 0.0028	0.0433	± 0.0021	0.0411	± 0.0036	
c_6	0.1470	± 0.0118	-0.0234	± 0.0091	-1.0736	± 0.0198	

Figure 5a shows the estimated fuel content of the individual tanks from LS model compared with the LUT estimates from one of the flights. Clearly the sudden jumps observed in the LUT estimates are not seen in the estimates from LS models. Fig.5b shows the total fuel content estimated by LS model and LUT compared with the reference DTOT. The error with respect to reference DTOT is also shown in the figure. The error plots indicate that total fuel estimation error by LS model is lower than that of LUT. Similarly Fig.6a shows the fuel content estimated from LS models compared with the LUT estimates from another post flight data with one probe failed in RHWT. In spite of the probe failure the fuel estimates by LS models show less variation. The total fuel estimates and their error with respect to DTOT reference is shown in Fig.6b which clearly indicate that the fuel estimation by LS models is more consistent and much closer to the reference value than the LUT estimates.

In order to assess quantitatively the impact of the coefficient estimation accuracies on the estimated fuel content in the tanks, the LS estimated fuel quantity are plotted with upper and lower bounds. Upper bound corresponds to fuel quantity estimation from 'LS coefficients + std deviation' and lower bound corresponds to fuel quantity estimation from 'LS coefficients - std deviation'. Fig.7 shows the plot of the fuel content estimated with bounds for one of the fuel tanks from three concatenated flight data sets. It can be observed from the figure that the estimated fuel content falls within the bound of ±10 kgs indicating that the accuracy of the estimated fuel content value could be anywhere within ±10 kgs in each tank.

Probe Failure Cases

Out of the 56 flight data used for LS model validation, 14 flights are with probe failure. In all these 14 flights only one probe failed either in wing tanks or in F1/F2 tank and out of 16 probes only few probes have failed repeatedly. Fuel estimation shown in Fig.6a and 6b is with one probe failure in one of the wing tanks, the results indicates that the fuel estimates using estimated LS models were not degraded with one probe failure in the wing tank. In order to ascertain the ability of the LS models to handle more probe failures, a sensitivity study was carried out by artificially introducing failures in the probes in post flight data. Different combinations of probe failures are simulated by setting the probe status to "Fail" in the fuel estimation algorithm while estimating the fuel content in the tank.

Probe Failures in Wing Tanks

In each wing tanks there are four probes, each comes under gauging at different fuel levels. First, forward immersed (FI) probe comes under gauging when the fuel is approximately in the range of 600 to 515 kgs, followed by forward top mounted (FT) probe when the fuel in approximately in the range of 470 to 150 kgs, then outer top mounted (OT) probe when the fuel is approximately in the range of 395 to 130 kgs, and finally aft immersed (AI) probe when the fuel in approximately in the range of 290 to 20 kgs. Different combinations of probe failures are simulated and used for estimation of fuel content in the wing tanks from the available flight data. From the analysis of probes failure in the wing tanks following points have been observed:

- Fuel content estimation is affected only in the region (that is fuel level) where the failed probe is under gauging.
- Among the four probes, AI probe which comes under gauging at the end plays a crucial role. It inflicts maximum error at the end if failed. If AI probe is working, often it helps in recovery at the end when other probe(s) fail.
- If all the probes in the wing tanks fail, the maximum error in total fuel content estimation is found to be around 400 Kgs.

Probe Failures in Fuselage Tanks

In F1A tank there is only one probe which is bottom mounted. If this probe fails there is no way to predict the correct fuel content in the tank.

The F1/F2 tank is a supply tank to the engine and it acts as a buffer between the wing tanks /F1A tank and the engine till the wing tanks and F1A tank becomes empty. Once wing tanks and F1A tank becomes empty and all probes in F1/F2 tank fail, fuel content in the F1/F2 tank can still be approximately computed based on fuel flow meter output. The effect of failure of three top mounted probes on fuel estimation in the F1/F2 tank is simulated and studied. It is observed that although all three top mounted probe failures affect the F1/2 tank fuel content estimation, its impact on the total fuel content estimation is less than 200kg in the worst case.

The LS model based fuel estimation has been implemented and tested on microcontroller based electronic unit which will be onboard the aircraft for in-flight fuel estimation [13].

Conclusions

This paper presents the least square models for aircraft fuel estimation. Least square coefficients have been estimated separately for each of the 16 fuel capacitance gauging probes present in the internal fuel tanks of the aircraft using noise filtered individual probe data, aircraft accelerations, attitudes and the reconstructed fuel content (of the tank in which the particular probe is located) data. Since accurate or directly measured time history of fuel content for each of the aircraft internal fuel tanks is not available from the flight data, for estimating the LS coefficients, the fuel content time history has been reconstructed using lookup table as well as flow meter output data. The estimated LS coefficients are subsequently used along with aircraft attitudes and accelerations to estimate fuel content in the fuel tanks. The LS model based fuel estimation algorithm utilizes other logics based on information on maximum fuel rate from each tank, FULL/EMPTY switch status, probe/switch threshold values, etc. to improve the accuracy/robustness of the fuel estimates. Data from 56 flights including the probe failure cases are used to verify the fidelity of estimated LS models in estimating the fuel content in the tanks.

LS models based fuel estimation algorithm is computationally simple (consists only multiplication and averaging) compared to the currently used table lookup method. From the fuel estimation results it is observed that the fuel estimates by LS models is low in fluctuations and closer to the reference value than lookup table estimates. Sensitivity of LS models to the probe failures have been studied with simulated probe failures in real data. From this sensitivity study it is observed that in wing tanks, fuel content estimation is affected only when the failed probe is under gauging. As a result, accuracy of fuel estimation in wing tanks is severely affected with multiple probe failures. Among the four probes in wing tanks, AI probe which comes under gauging at the end plays a crucial role, its failure inflicts maximum error at the end and often it helps in recovery at the end when it is working and other probe(s) fail. In case of F1A tank, as there is only one probe, failure of this probe can totally affect the fuel estimation of that tank. In F1/F2 tank, if all the three top mounted probes fail, it is still possible to estimate the fuel content with an error of 100 to 150 kgs.

Acknowledgements

This work is sponsored by Aeronautical Development Agency, Bangalore. Authors acknowledge Mr. Shyam Chetty, Director, National Aerospace Laboratories (NAL) and Project Director (GS), Aeronautical Development Agency (ADA) for providing opportunity and encouragement to work on this critical problem of in-flight fuel estimation for fighter aircraft. Authors also acknowledge Mr. V Krishna Prasad, Scientist, ADA, Ms P Usha, Scientist, ADA, Ms Manjula, Manager, Design, Hindustan Aeronautics Limited (HAL) and Ms. Malini, Deputy Manager, Design, HAL for providing data/information and useful discussions.

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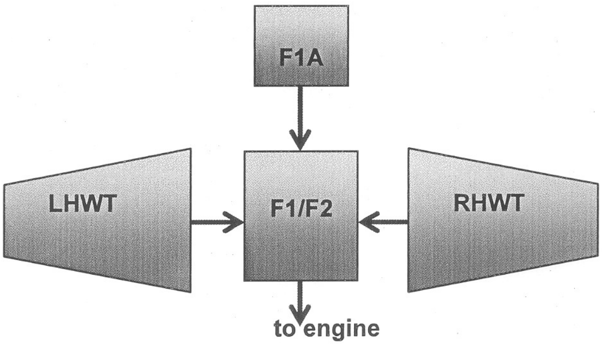

Fig.1 Aircraft Fuel Tank Arrangement

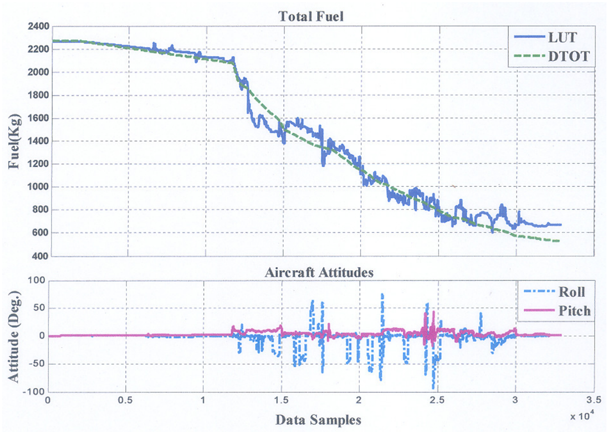

Fig.2 Comparison of Estimated Fuel Content by LUT Method with DTOT Reference

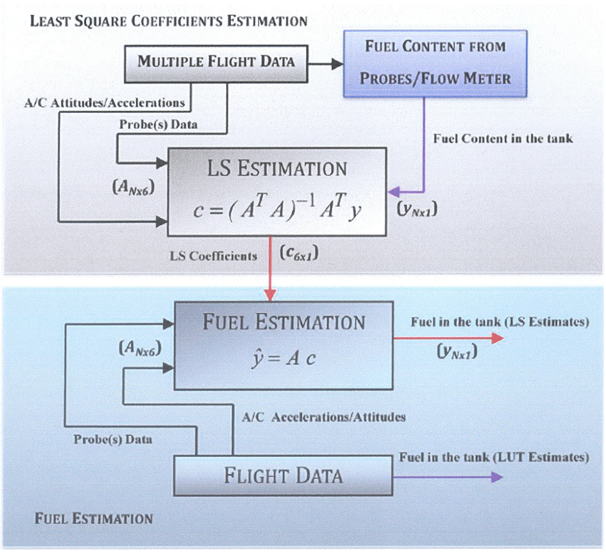

Fig.3 Fuel Estimation by Least Squares Method

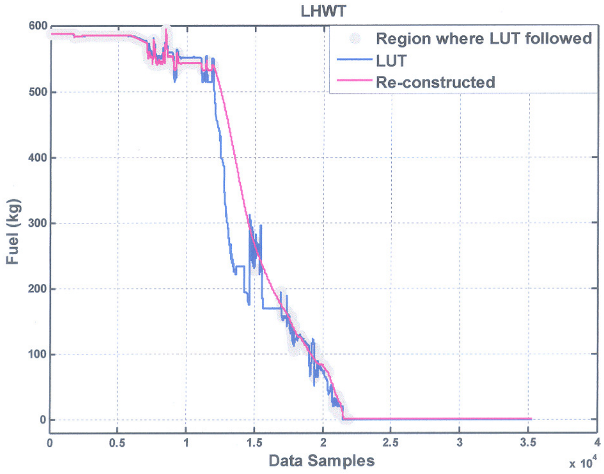

Fig.4 Reconstructed Time History of Fuel Content

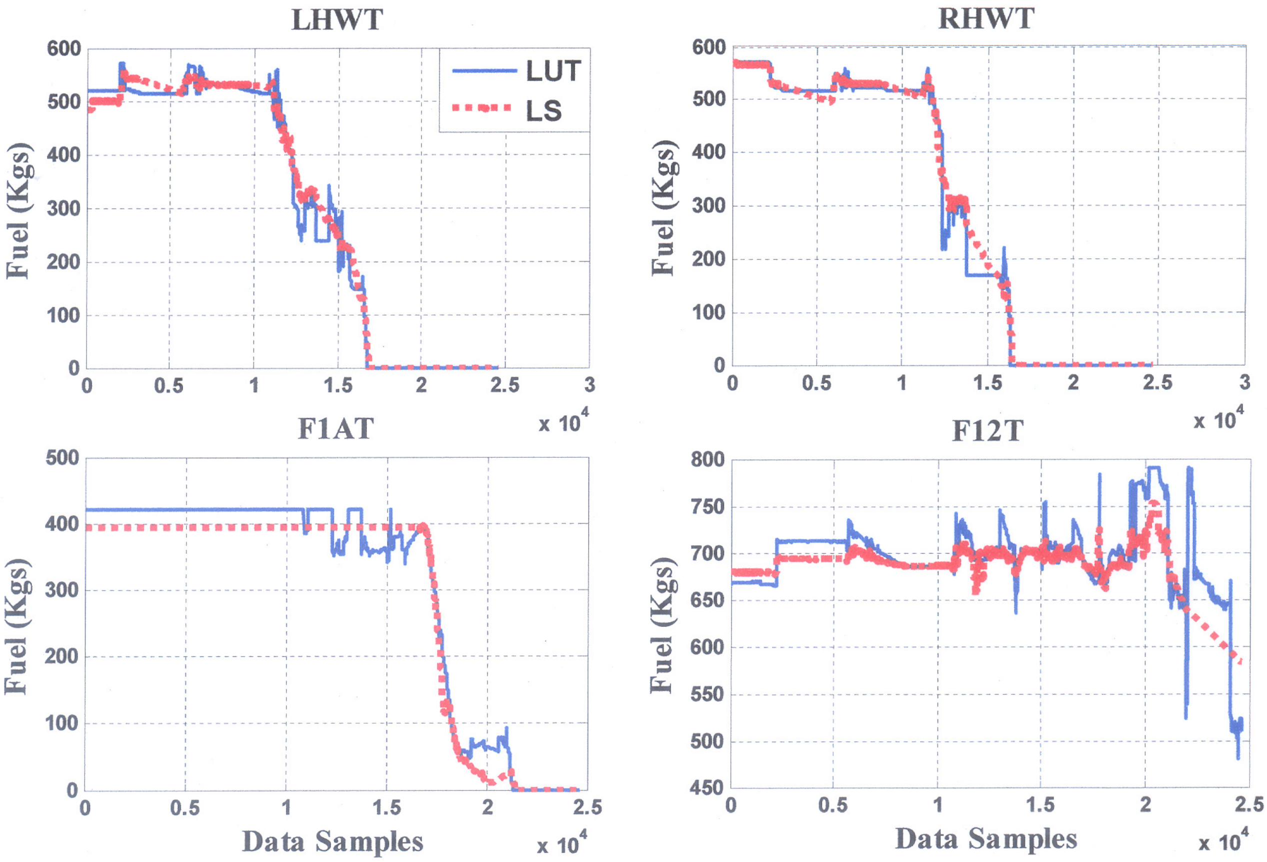

Fig.5a Estimated Fuel Content in Individual Tanks from Flight Data without Probe Failure

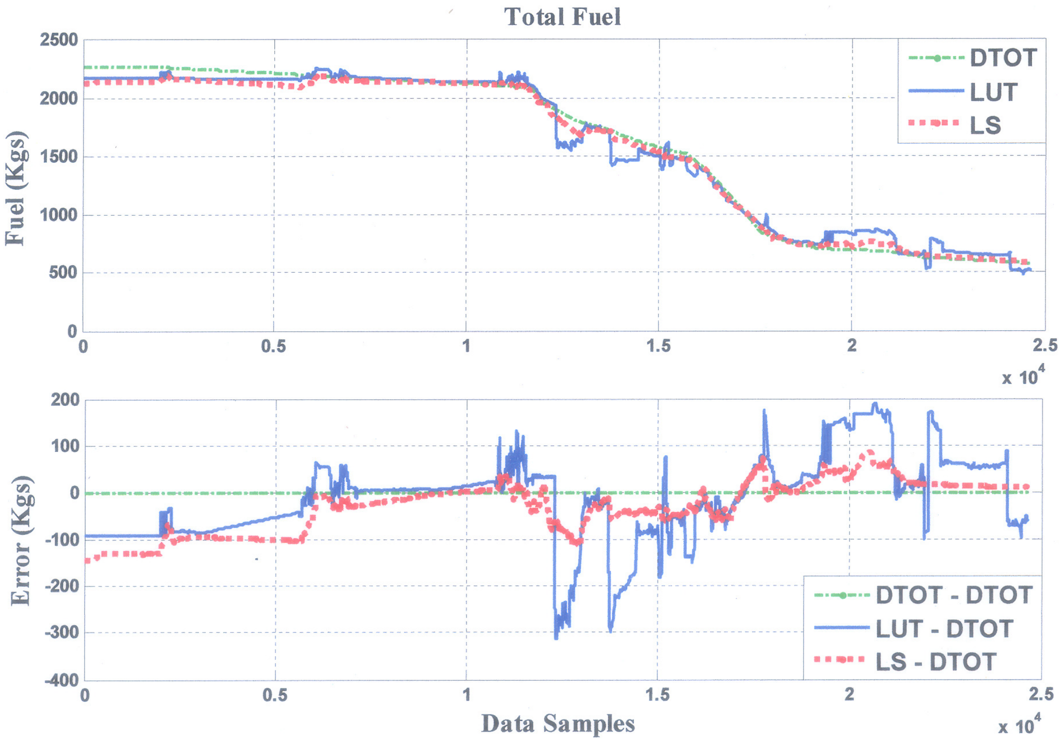

Fig.5b Total Fuel Content Estimates and their Error without Probe Failure

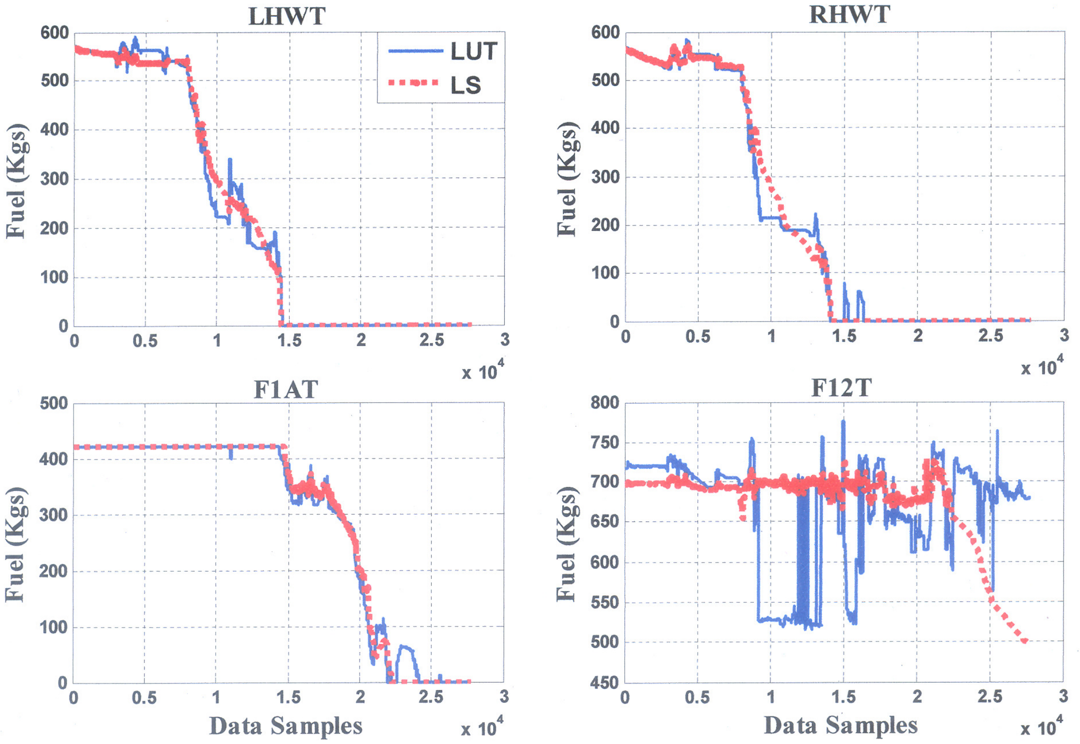

Fig.6a Estimated Fuel Content in Individual Tanks from Flight Data with one Failed Probe

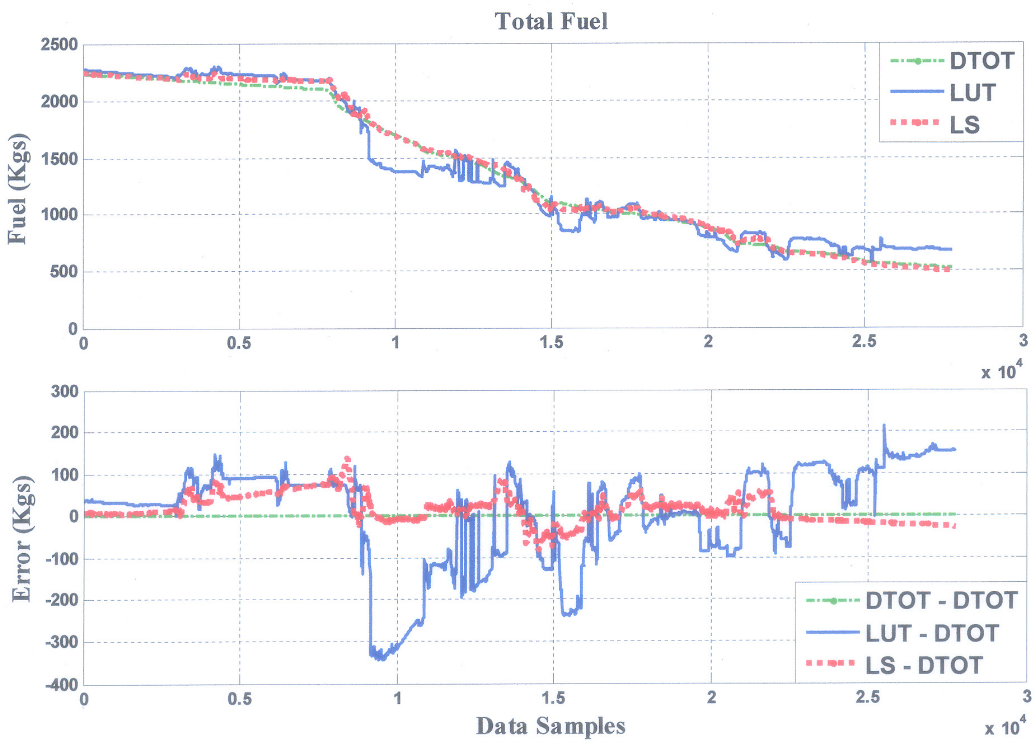

Fig.6b Total Fuel Content Estimates and their Error with one Failed Probe

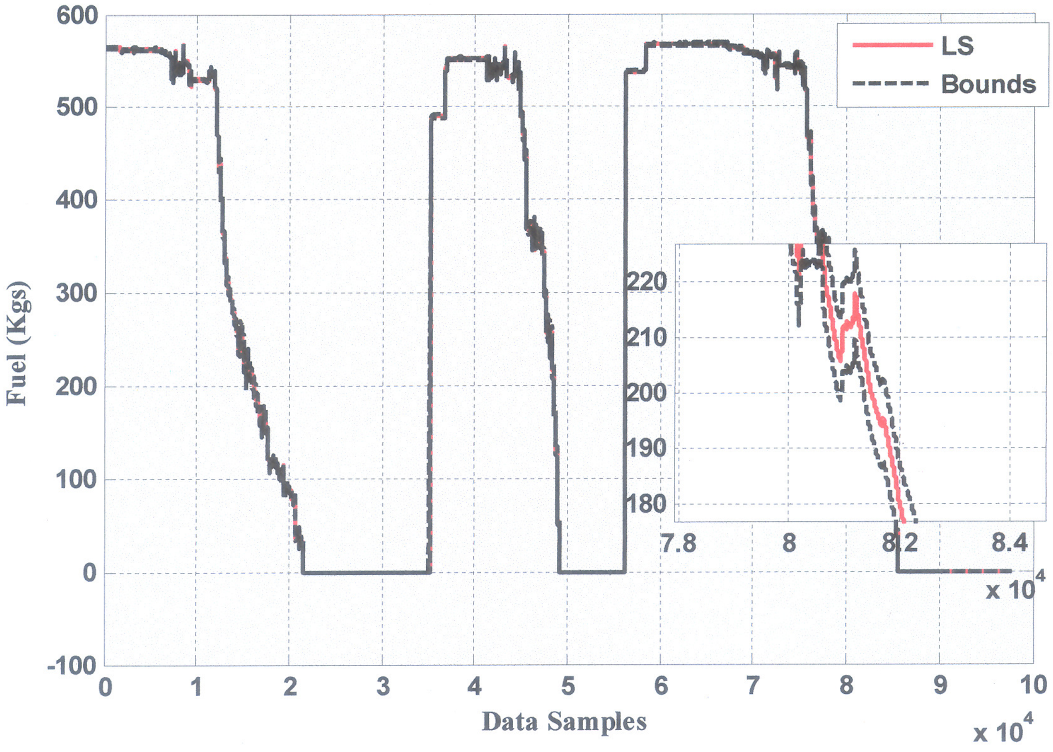

Fig.7 Fuel Estimates from LS Models with Bounds