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A STUDY ON MODELING TECHNIQUES FOR FUEL BURN ESTIMATION BASED ON FLIGHT SIMULATOR EXPERIMENT DATA

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ABSTRACT

The ever-increasing demand for global air travel provokes many daunting challenges for the aviation industry in meeting future requirements. Estimation of fuel consumption plays a central role in aircraft performance evaluation, which is vital in understanding and validating key components of a future air traffic management system. This study provides a framework for a quantitative evaluation on fuel burn estimation with the objective of proposing modeling techniques to accurately assess the aircraft performance. Data from a series of continuous descent operations simulations conducted on full-flight simulator are used as reference data. Base of Aircraft Data (BADA) aircraft performance model data provided by Eurocontrol are integrated with point mass dynamics to estimate fuel flow in both clean and non-clean configurations of the aircraft. Statistical results show the model can estimate the total fuel consumption within ±6% of actual value with ±6% and ±10% for cruise and descent phases respectively.

1 INTRODUCTION

The ever-increasing demand for global air travel provokes many daunting challenges towards operators, regulators and navigation service providers in the aviation industry. Circumstantially, various research & development projects which promote the transition of the current airspace-based air traffic control (ATC) system into a more flexible and reliable air traffic management (ATM) system are conducted in a global scale. Collaborative Actions for Renovation of Aircraft Systems, commonly known as CARATS is the counterpart for the NextGen of United States and SESAR of Europe and serves as the long-term research roadmap established by the Japan Civil Aviation Bureau (JCAB) for the renovation of Japan's national air transportation system (Study Group for the Future Air Traffic Systems 2010). One of the key challenges of the roadmap is to increase the operational capacity of the Tokyo International Airport, which handles the 5th largest annual passenger enplanements in the world (Airports Council International 2015). 4D-Trajectory Based Operations (4D-TBO) and Continuous Descent Operations (CDO) are two of the core technologies proposed in the roadmap to increase the efficiency and reliability of a possible future system. Authors have contributed towards the improvement of CARATS through evaluating potential benefits of a future ATM system with ideal operational environment via trajectory optimization (Wickramasinghe et al. 2016) and proposing optimal arrival methodologies to address the challenges in terminal and airport surface operations (Toratani, Wickramasinghe and Itoh 2017).

Modeling of aircraft motion and reference to aircraft performance data are crucial aspects for accurate evaluation of aircraft performance. In particular, precise modeling of aircraft performance in non-clean configuration or low-altitude operations is critical. Extensive research streams in recent years have focused on accurate modeling of aircraft performance. Trani et al. (2004) used a neural network approach to estimate fuel burn which required large database of aircraft operations and state data. Patterson et al. (2009) provided a preliminary analysis on the accuracy of fuel burn models by comparing real-time aircraft flight data and International Civil Aviation Organization (ICAO) time-in-mode method. Results showed different fuel flow-rate patterns for a majority of flights than the ICAO standard data. This is confirmed through an analysis conducted by Chati and Balakrishnan (2014) on aircraft fuel burn and emissions in the landing and take-off cycle using FDR data. Senzig, Fleming and Iovinelli (2009) proposed a thrust specific fuel consumption (TSFC) model based on a airplane manufacturer data and shows estimation accuracy of ±5% from field elevation up to 10,000 ft. However, the requirement of detailed data from manufacturers limit the general application of this model. Oaks, Ryan and Paglione (2010) proposed a fuel burn model for a prototype application which could estimate the fuel consumption 2% more in ascent, 4.7% more in cruise and 37.1% less in descent respectively compared to data from a flight data recorder (FDR). Chatterji (2011) introduced a detailed model to estimate fuel burn and validated the estimation at a deviation less than 1% compared to data from a flight data recorder (FDR) of a single flight. Lack of aircraft performance data were generated through scaling the average values of performance data from other aircraft and these parameters were fitted through trial and error to achieve the model's accuracy. Also, the application of a proportional-integral-derivative (PID) controller based estimator reduced the noise in estimated parameters. This type of high-order estimator requires significant computations to define the appropriate gain values. Harada et al. (2013) used a point mass approach to quantitatively evaluate the fuel consumption and denoted an accuracy of ±5% only in clean configuration. Most of these studies refer to the Base of Aircraft Data (BADA) Family 3 database of Eurocontrol due to its vast coverage of currently operated aircraft, simplicity and availability. This model is well adapted for large-scale, high-level performance simulations which mainly focus on substantial accumulative data. In case when a single aircraft is extensively reviewed for its entire flight envelope, referring to a performance database which features in-depth performance data for all configurations is crucial. BADA Family 4 database provides such a platform and is applied in this study.

Fuel burn estimation models tailored to address various issues have contributed, and continue to contribute as the key performance indicator in aircraft performance evaluation. This paper provides a framework for a quantitative evaluation on fuel burn estimation as an enhancement for aircraft performance evaluation through accurately assessing the fuel consumption. Data from a series of full-flight simulator experiments conducted for continuous descent operations (CDO) demonstrations are used to validate the computational results obtained from the proposed model. Point mass dynamics are integrated with BADA Family 4 database to develop a computationally efficient and accurate aircraft performance model. Phase-wise fuel burn computations are implemented and the deflections from measured values are statistically reviewed to investigate the validity of the proposed model. The objective of this study is to provide a generalized and accurate platform for various aircraft performance evaluations conducted at ENRI.

The structure of this paper is as follows. Section 2 introduces the reference data and aircraft performance model including mathematical formulation and model structure used in the analysis. Section 3 shows results on fuel consumption computations at different flight scenarios along with results from the statistical analysis on model accuracy. Discussion on obtained results and further improvements of the model are provided in section 4. Section 5 summarizes the study with the conclusion.

2 DATA SOURCES AND MODELS

This section introduces the reference data used in the study and discusses the fuel flow estimation procedure with referring to mathematical formulation of aircraft motion and model integration with BADA database. Since the reference data are obtained from full-flight simulator experiments, International Standard Atmosphere (ISA) conditions are considered in the analysis.

2.1 Full-Flight Simulator Data

Flight data from a series of flight experiments conducted in a full-flight simulator with the collaboration of a national airline are used as reference data in this study (referred to as 'measured data' herewith). The objective was to review the operational feasibility of FPA descent procedures (Itoh et al. 2016) and the experiments included various conventional (OPD, vectoring, adjustment of required time of arrival (RTA) etc.) and concept-based (FPA descent, continuous climb operations (CCO) etc.) operational scenarios implemented at Tokyo International Airport (ICAO code: RJTT) and Kansai International Airport (ICAO code: RJBB). A total of 48 flight trials were corroborated for a twin-engine wide body jet passenger aircraft. This data series provides a broad platform to model the aircraft performance in various configurations. Figure 1 illustrates an example of arrival routes assigned to RJTT in the experiments. Data related to aircraft states are used to estimate aerodynamic drag, engine thrust and fuel flow rate while performance parameters are used to validate the proposed model.

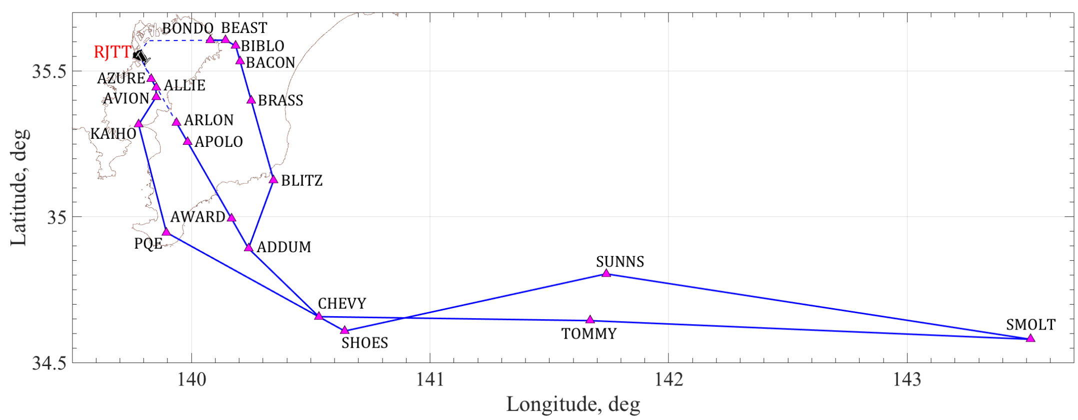

Figure 1: Arrival routes at Tokyo International Airport (RJTT) used in the experiments.

2.2 Meteorological Data

As mentioned earlier, ISA conditions are applied in the experiments. Wind data obtained from Global Spectral Model (GSM) are used in the simulations where wind data (magnitude and direction) are set at four levels of pressure altitude through the simulator's flight management system (FMS). Wind conditions are set in the simulator with a linear approximation as illustrated in Figure 3, where wind speed

Figure 3: Setting of wind magnitude and wind direction.

and wind direction are plotted against pressure altitude extracted from a simulation flight conducted at RJBB. Wind magnitudes are given at MADOG, SUC, EVIAN and MAYAH fixes.

2.3 Mathematical Formulation of Aircraft Motion

Point mass approximations are considered in this study to model the aircraft's 3-D translational motion. Generally, three governing equations are used to describe the aircraft's motion of where longitude θ, latitude ϕ and geometric altitude h are respectively defined in (1) – (3) as,

$$\dot{\phi} = \frac{1}{R_0 + h}(V_{TAS} \cos\gamma_a \cos\psi_a + W_{SN}) \tag{1}$$

$$\dot{\theta} = \frac{1}{(R_0 + h)\cos\phi}(V_{TAS} \cos\gamma_a \sin\psi_a + W_{EW}) \tag{2}$$

and

$$\dot{h} = V_{TAS} \sin\gamma_a \tag{3}$$

with, R_0 as the mean radius of Earth, V_{TAS} as the airmass-relative speed or true airspeed, γ_a and ψ_a as airmass-relative flight path angle and azimuth angle. W_{EW} and W_{SN} respectively denote the zonal and meridional wind components acting on the aircraft.

The definition of aircraft's acceleration due to acting forces on its body varies according to the coordinate frame of reference. Previous studies show that using an inertial coordinate frame results significant noise on the estimated inertial speed (Harada et al. 2013), which occurs due to the measurement noise of ground speed and amplifies due to the consideration of time derivative. Hence, an airmass-relative coordinate frame was used in this study and the airmass-relative acceleration of the aircraft is defined from

$$m\frac{dV_{TAS}}{dt} = T - D - mg\sin\gamma_a - m\left(\frac{dW_{EW}}{dt}\sin\psi_a + \frac{dW_{SN}}{dt}\cos\psi_a\right)\cos\gamma_a \tag{4}$$

where m is aircraft mass, T is required thrust, D is aerodynamic drag and g is the gravitational acceleration with the angle-of-attack is assumed zero. When assuming the vertical component of wind is negligible, an apparent force corresponding to the rate of change of wind acts upon the moving coordinate frame. As (4) represents the force equilibrium along the true airspeed vector, the apparent force component can be included in the equation as shown within parentheses. Furthermore, to reduce irregularities of true airspeed a weighted difference approximation is used as shown in (5) where the time derivative of true airspeed at time t_i can be derived as

$$\frac{dV_{TAS}}{dt}(t_i) = \sum_{j=1}^{n}\frac{2}{n}\left(\frac{n+1-j}{n+1}\right)\frac{V_{TAS}(t_{i+j}) - V_{TAS}(t_{i-j})}{2j\Delta t} \tag{5}$$

where the subjected time interval was ± 5s ($n = 5$) in this study.

2.4 Aircraft Performance Model

BADA Family 4 database is used as the primary reference for aircraft performance model in this study. BADA consists of a aircraft performance model which is based on a mass-varying, kinematic approach (Eurocontrol Experiment Centre 2016) and unlikely its counterpart BADA Family 3, BADA Family 4 defines its aerodynamic, thrust and fuel flow models in the form of polynomial expressions with extensive reference to different flight profiles and configurations of the aircraft. Another significant difference is that most of the mathematical models are derived as functions of Mach Number M.

Aerodynamic drag D is generally computed by using the drag coefficient C_D and the mathematical expression is given in (6) as

$$D = \frac{1}{2}\kappa p_0 S \delta M^2 C_D \tag{6}$$

where κ is adiabatic index, p_0 is standard atmospheric pressure at mean sea level, δ is pressure ratio (ratio between pressure at aircraft's position and p_0) and S is wing reference area. C_D is computed as a function of lift coefficient C_L, position of high-lift devices δ_{HL}, position of speed brakes δ_{SB} and M, which is generalized as

$$C_D = f(C_L, \delta_{HL}, \delta_{SB}, M). \tag{7}$$

The general formulation of fuel flow rate can be defined as,

$$FF = \delta \cdot \theta^{\frac{1}{2}} W_{MTOW} \cdot a_0 \cdot L_{HV}^{-1} \cdot C_F \tag{8}$$

where θ is temperature ratio (ratio between temperature at aircraft's position and temperature at mean sea level in ISA), W_{MTOW} is maximum take-off weight, a_0 is speed of sound at mean sea level in ISA, L_{HV} is the fuel lower heating value and C_F is fuel coefficient. C_F is usually computed according to engine's non-idle and idle thrust ratings where the corresponding value is usually acquired by,

$$C_F = \begin{cases} C_{F,idle} & \text{idle ratings is used} \\ \max(C_{F,gen}, C_{F,idle}) & \text{non} - \text{idle ratings is used} \end{cases} \tag{9}$$

where $C_{F,idle}$ is the idle fuel coefficient and $C_{F,gen}$ is the non-idle or general fuel coefficient. Since the engine rating flag was not included in the reference data, the maximum value was selected for the whole process. Thus, $C_{F,idle}$ and $C_{F,gen}$ are generally expressed as,

$$C_{F,idle} = f(M, \delta, \theta) \qquad C_{F,gen} = f(M, C_T) \tag{10}$$

where C_T is the thrust coefficient. C_T can be computed by the relation of,

$$T = \delta \cdot W_{MTOW} \cdot C_T \tag{11}$$

C_T is generally expressed as a function of Mach Number and throttle parameter for non-idle ratings (maximum cruise, maximum climb and maximum take-off) and no rating (direct throttle parameter input) and as a function of pressure ratio and Mach Number for idle ratings of a turbofan engine. These formulae are used for trajectory modeling and (11) is used in the study as the engine thrust is already an estimated parameter. As the reference data is obtained at a frequency of 1 Hz, the total fuel consumption (TFC) is obtained as the time integral of fuel flow rate, which can be derived as

$$TFC = \sum_{t=0}^{t_f} FF(t) \cdot \Delta t \tag{12}$$

where Δt is the time interval and t_f is the terminal time of the flight.

3 ANALYTICAL RESULTS

This section discusses the validity of the proposed aircraft performance model based on a conducted quantitative evaluation on fuel burn estimation. Figures 4 and 5 illustrate two examples, first example (flight 35) with a smooth descent with no speed restrictions and the 2nd example (flight 15) with a series of speed commands given during descent. These respectively represent a standard performance modeling and a performance modeling in largely varying conditions.

In each plot, the top figure indicates pressure altitude and, measured and estimated fuel flow rates while the bottom figure indicates the use of speed brakes, flaps and landing gear extension. All the parameters are plotted against the flight time. Flight 35 includes the deployment of speed brakes and flaps at 5 degrees where the flight is implemented only up to the initial approach fix (IAF). Flight 15 was conducted for FPA descent with speed control as a demonstration of flight-deck interval management (FIM). Large fluctuations in fuel flow rate have occurred due to various speed commands given to the pilot. Fuel flow rate increased largely right before the flight termination due to the full deployment of flaps and landing gear which increases the aerodynamic drag significantly. Both figures denote that the fuel flow rate instantly increases with the deployment of flaps and, landing gear in case of flight 15. Speed brakes are deployed to decrease the airspeed but fuel flow rate is not affected due to the idle thrust conditions. The position of landing gear is usually recorded between 0 and 1 and the value is multiplied by 20 in this study for better visibility in the plots. Time histories of measured and estimated fuel flow rates indicate that the proposed method could model the aircraft's behavior with a considerable degree of accuracy. Figure 4 indicates that the relaxed conditions of the aircraft were modeled by the proposed method with a high accuracy with a slight deflection at the deployment of flaps. Figure 5 shows that the proposed method could take the speed variations into account where large fuel flow ratings were tracked with high accuracy. Significant difference is noted in the descent phase fuel flow rate compared to studies conducted on aircraft performance with BADA 3 model. Top figures in Figures 4 and 5 show that the inclination of descent fuel flow rate is inversely proportional to flight altitude. This is due to the increase

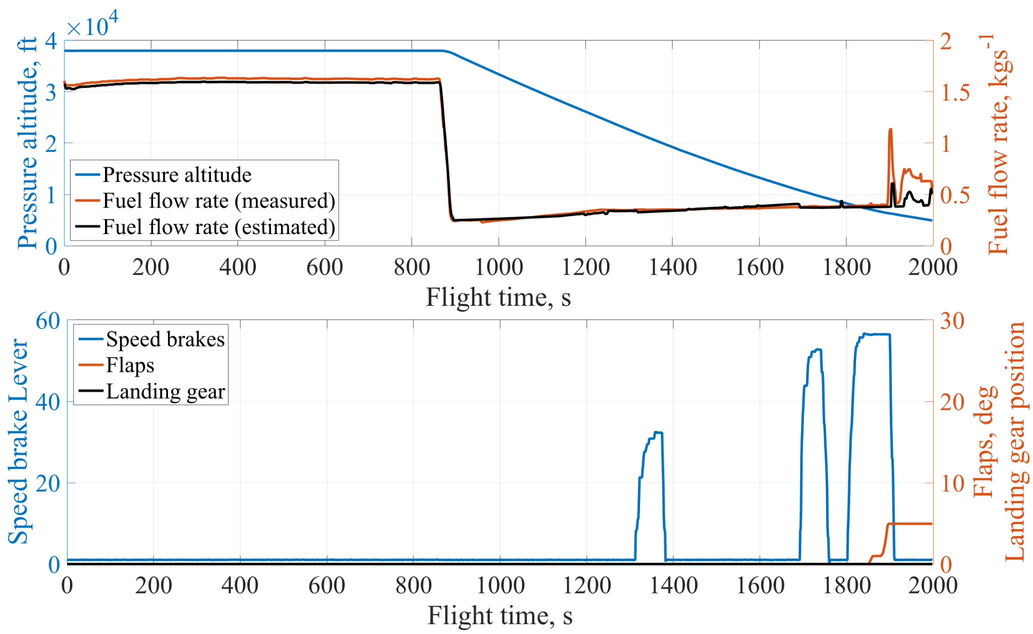

Figure 4: Fuel flow rate estimation and related time histories for Flight 35 (Top: Pressure altitude, measured fuel flow rate and estimated fuel flow rate. Bottom: Speed brake lever, flaps and landing gear).

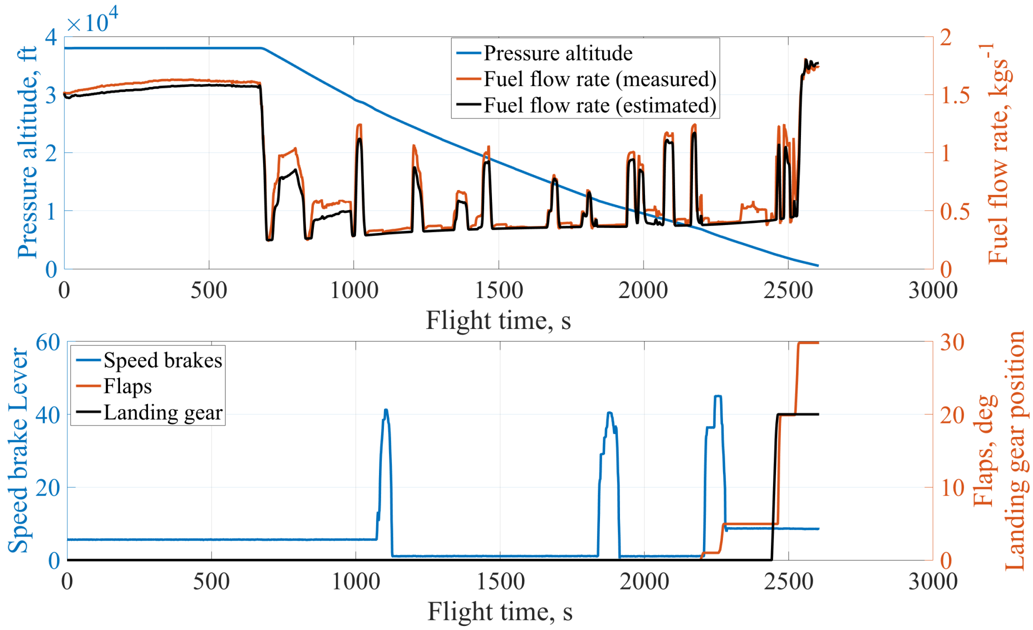

Figure 5: Fuel flow rate estimation and related time histories for Flight 15 (Top: Pressure altitude, measured fuel flow rate and estimated fuel flow rate. Bottom: Speed brake lever, flaps and landing gear).

in air density with the decrement of altitude. Harada et al. (2013) and Wickramasinghe et al. (2016) express that the increment of estimated descent fuel flow rate deviates significantly, even in the clean configuration, from measured data due to the simplified function of geopotential altitude defined in BADA 3 model for fuel flow rate computations in idle thrust conditions. On the other hand, BADA 4 model computes the idle rating fuel flow rate by (10) which considers not only altitude (pressure and temperature ratios), but also speed. This results a high accuracy in modeling idle thrust conditions which can be noted from the given two examples. The measured TFC for Flight 35 was 1833kg while the estimated TFC from the proposed method was 1778kg causing a difference of 55kg at an estimation error of -3.1%. For Flight 15, the measured TFC was at 2195kg while the proposed model estimated the TFC at 2047kg with a difference of 148kg with an estimation error of -6.7%. The estimation error percentages are obtained from

$$err_{TFC} = \frac{TFC_{est} - TFC_{data}}{TFC_{data}} \times 100\% \quad (13)$$

where err_{TFC} indicates the estimation error, TFC_{est} is the estimated TFC and TFC_{data} is the measured TFC.

Figure 6 provides the statistical review on the estimation error. Top figure denotes the fuel flow rate estimation error at each data point for all the flight cases using a whisker plot presentation. In whisker plot, the red horizontal line within each box indicates the median value, the upper and lower edges of the box indicate the 1st and 3rd quartiles (includes 50% of the normal population). The interquartile range (IQR) is the data between 1st quartile and 3rd quartile. Lower and upper whiskers cover 99.3% of the normal population which is the data range between "1st quartile – 1.5×IQR" and "3rd quartile + 1.5×IQR". The extremals or outliers are indicated with red markers which are beyond the lower and upper limits of whiskers. Results show that the average median of the estimation error for all flights is -0.023 kg/s. The average IQR is from -0.035 kg/s to -0.050 kg/s. In most flight cases outliers are included within ±1kg/s. The bottom figure denotes the root mean squared error (RMSE) and mean error of each

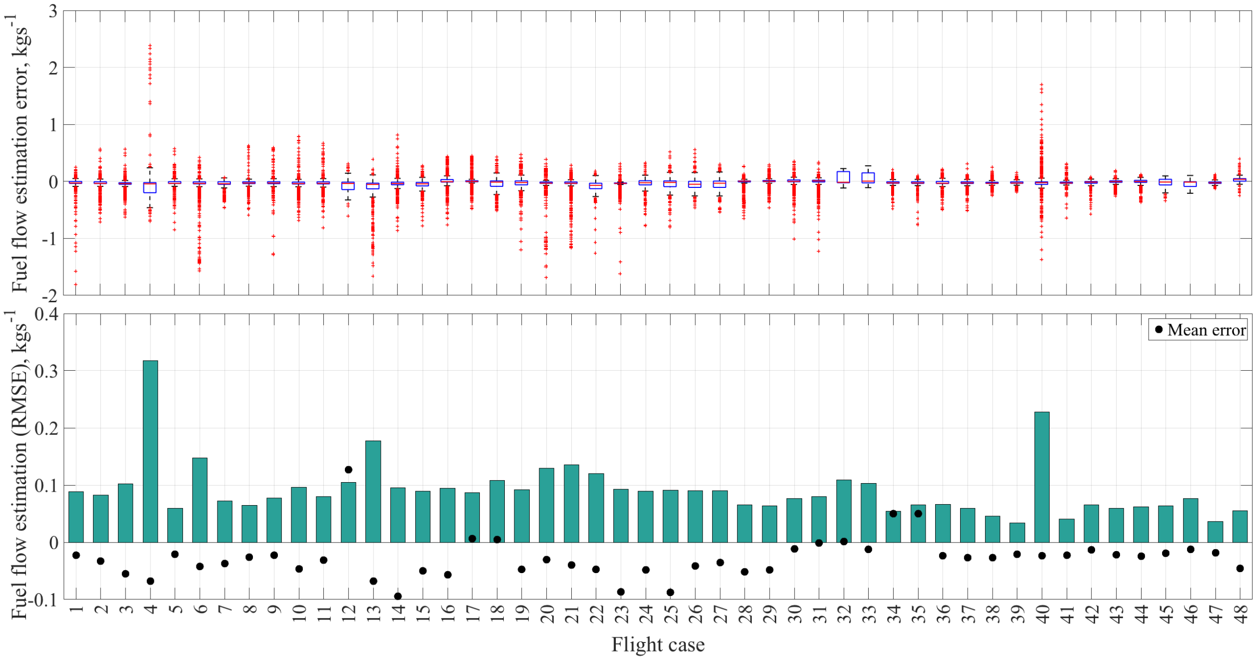

Figure 6: Estimation error of fuel flow rate (Top: Boxplot presentation. Bottom: Root Mean Squared Error (RMSE) and Mean error).

flight case. The average RMSE and mean error for all 48 flights are 0.091kg/s and -0.028kg/s respectively. These Results indicate that the BADA 4 model provides high accuracy in aircraft performance modeling and fuel burn estimation. Also, results depict that the proposed model has a tendency in under-estimating the instantaneous fuel flow rate. One of the reasons is assumed to be the distinction of aircraft performance due to the distinction of engine models applied in full-flight simulator and BADA 4 database.

Furthermore, a phase-wise estimation error evaluation was conducted to review the impact of configuration setting in fuel burn estimation. Since the take-off and climb phases are not considered in the experiments, fuel flow rates only at cruise and descent phases are investigated. Figure 7 illustrates the results from this review with an error bar expression. Error bars depict the standard deviation of each estimation with red and blue colors respectively representing the results of cruise and descent phases. Standard deviation in estimation error σ_{err} is obtained by,

$$\sigma_{err} = \sqrt{\frac{1}{n-1}\Sigma\{FF_{err}(t) - \overline{FF_{err}}\}^2} \tag{14}$$

where FF_{err} is the estimation error and $\overline{FF_{err}}$ represents the mean of FF_{err}. Also the solid lines with markers represent the estimation error RMSE at each phase. Overall results show that the fuel flow rate estimation in descent phase has a larger contribution in estimation error results given in Figure 5. One reason is that each experiment commenced at an intermediate point at cruise phase, causing the cruise phase to be a short segment. Also, the most apparent reason is the deployment of high-lift devices, speed brakes and landing gear in descent phase compared to the clean configuration at cruise phase. The average standard deviation and RMSE in cruise phase estimation error are 0.041kg/s and 0.07kg/s while the corresponding values in descent phase are 0.087kg/s and 0.098kg/s respectively.

Finally, the fuel consumption estimation error is reviewed for total flight profile and phase-wise flight profiles as illustrated in the Figure 8. The top figure indicates the estimation error percentage of TFC, the

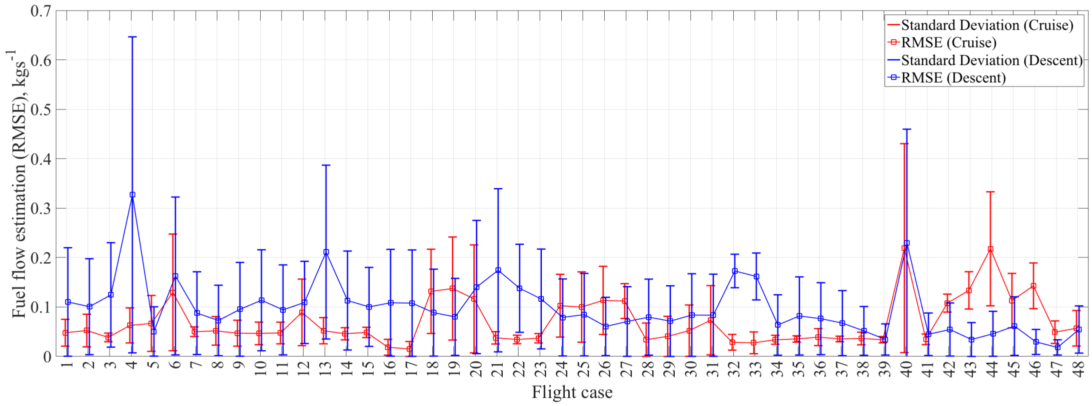

Figure 7: Estimation error evaluation on phase-wise fuel flow rate.

center figure indicates the estimation error of cruise phase fuel consumption and the bottom figure depicts the estimation error of descent phase fuel consumption. The average estimation error of TFC is -3.67% where the TFC was estimated at the range of ±6% except for Flights 4, 10, 13 and 22. The cruise phase fuel consumption is estimated at an average of -3.089% with the range of ±6% of measured data except for these four flights. Descent phase fuel consumption results show two irregular flight cases (Flights 32 and 33) with large positive deviation from measured data where the estimated fuel flow rate had a constant deflection from the measured data. Considering the rest of the flight cases, the estimation error is computed in the range of ±10% of measured data except for one flight case. The two irregular flight cases that result large deviation in descent phase fuel burn estimation are excluded from the overall discussion.

4 DISCUSSION

Observing the results explained in section 3, it is considered that the proposed aircraft performance model possesses sufficient accuracy in modeling aircraft's performance at clean and non-clean configurations. This study broadens the scope to address various modifications that would increase the proposed model's

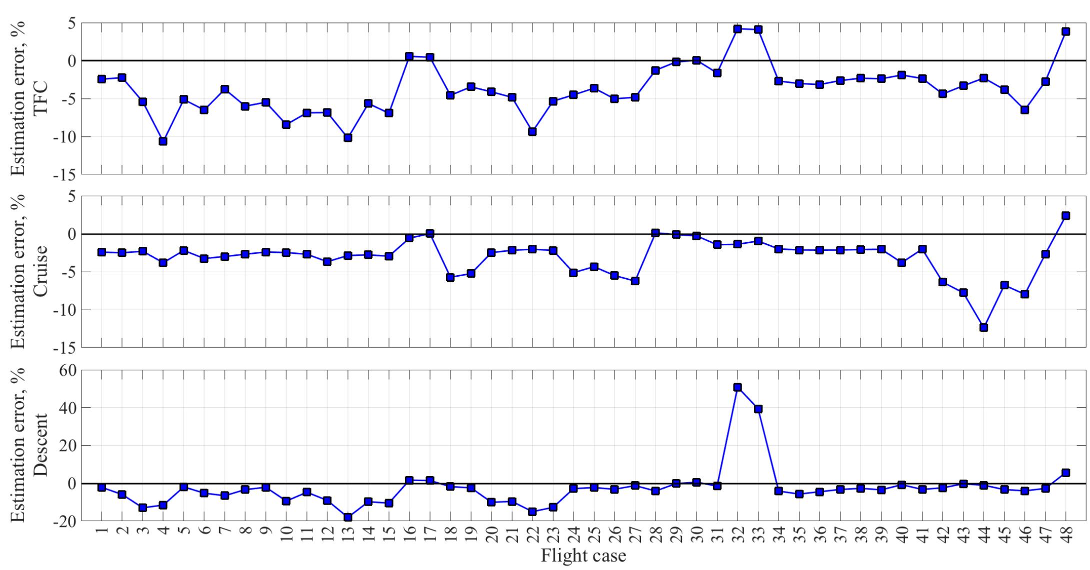

Figure 8: Estimation error of fuel consumption (Top: TFC. Center: Cruise phase. Bottom: Descent phase).

feasibility as a platform to review aircraft's performance in other applications (Kageyama and Akinaga 2017; Toratani et al. 2017). One improvement is to consider 6 degree-of-freedom (6-DOF) motion of aircraft in the mathematical formulation. This could be a potential solution to reduce the estimation error at low altitude which includes large heading variations and vectoring. A further analysis is required to understand how the FMS computations are integrated with aircraft's physical motion and procedure settings. Some flight cases express significant partial deflections in measured and estimated fuel flow rates due to the distinction between governing dynamics model in the proposed method and flight procedure settings in the FMS. Time histories of Flight 4 are shown in Figure 9 in which the estimated fuel flow rate displays a sudden partial deflection in descent phase compared to the measured value. Top figure denotes pressure altitude, measured and estimated fuel flow rates, center figure shows the thrust components in (4) which are defined as,

$$\text{Term } 1 = D, \quad \text{Term } 2 = mg\sin\gamma_a, \quad \text{Term } 3 = m\frac{dV_{TAS}}{dt}$$

$$\text{Term } 4 = m\frac{dW_{EW}}{dt}\sin\psi_a\cos\gamma_a, \quad \text{Term } 5 = m\frac{dW_{SN}}{dt}\cos\psi_a\cos\gamma_a$$

and the bottom figure illustrates Mach Number, pitch angle and flight path angle. Overall, similar characteristics are seen in the proposed model as in Figure 4. However, the estimated fuel flow rate has a rapid peak compared to the measured fuel flow rate just before 300s to the flight. Data express that a rapid change in flight path and pitch angles with a decrease in Mach Number which result the Term2 to hold a large negative value causing negative thrust. Hence the general fuel coefficient is given as a function of

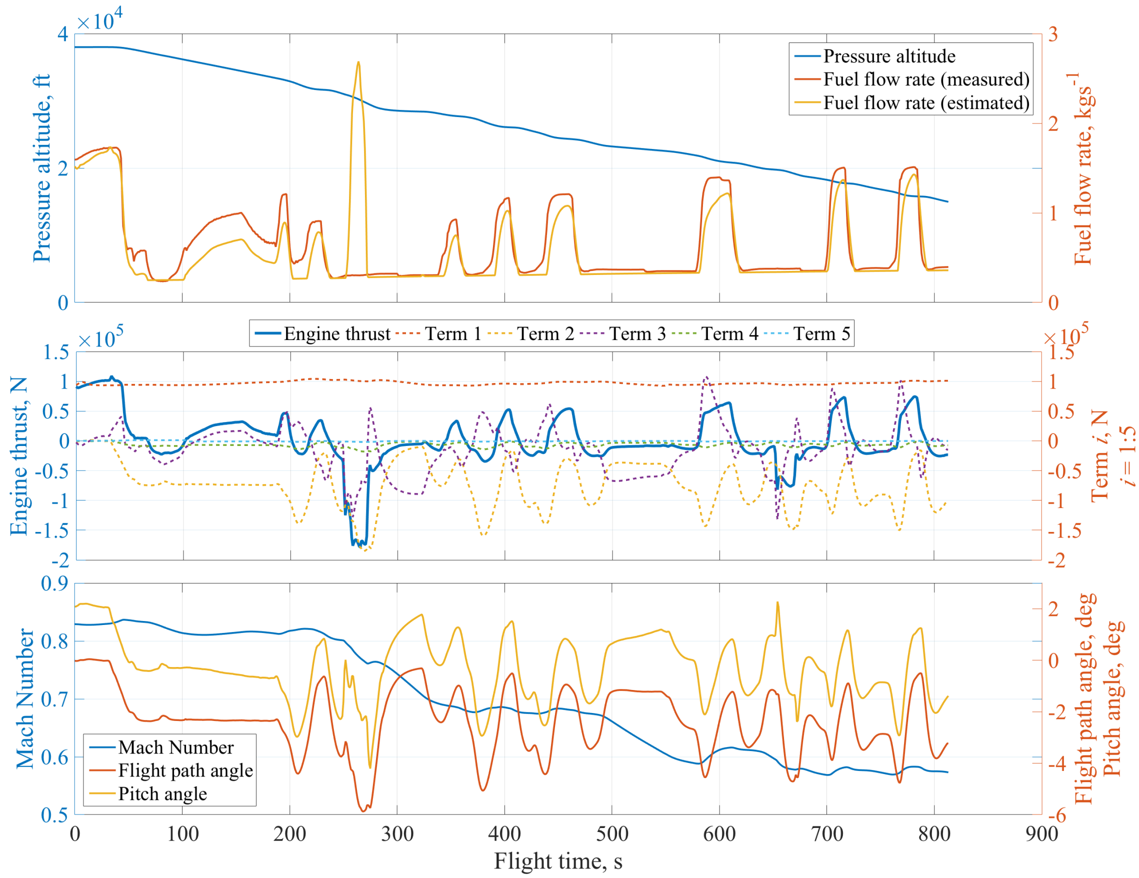

Figure 9: Time histories of performance parameters in Flight 4 (Top: Pressure altitude, measured and estimated fuel flow rate. Center: Thrust components. Bottom: Mach Number, flight path angle and pitch angle).

thrust coefficient which is computed as a polynomial of thrust causes the estimated fuel flow rate to increase rapidly. On the other hand, aircraft usually remains at idle thrust during descent leg and these procedure settings cause the measured fuel flow rate not to fluctuate with such changes in aircraft dynamics. How to integrate such procedure settings in the proposed method remains as a future work of this study.

Furthermore, the study subjects a single aircraft type and the scope of the proposed model is to be broadened by applying it into experiments that are conducted with different aircraft types. This would also provide a conclusion to investigate the impact of engine model difference in estimation process. Also, data from cockpit's quick access recorder (QAR) will be used as reference data that provides access to aircraft's total flight profile in non-ISA conditions. This would provide a comprehensive review on the proposed model's feasibility in modeling aircraft's performance from take-off to landing.

5 CONCLUSION

This study proposed a method to model aircraft's performance with a quantitative evaluation on fuel burn estimation. Data from a series of flight experiment data conducted in full-flight simulator was used as reference data to investigate the proposed model's accuracy and validity. Point mass approximations are used to model aircraft dynamics and BADA 4 model was used as the primary database for aircraft's performance reference. Fuel burn was estimated for a total of 48 flights and a statistical evaluation on the estimation error was conducted. Analytical results show that the proposed model is capable of estimating the fuel flow rate at an average of -0.028 kg/s. Results also depict that the proposed model has a tendency of under-estimating the fuel flow rate. The difference in engine models used in flight simulator and BADA 4 model is considered to be the main contributor to this conclusion and the model is to be tested with other aircraft types for clarity. Phase-wise review on estimation error shows that descent phase contributes largely to the estimation error due to the inclusion of non-clean configuration of aircraft. Furthermore, a quantitative evaluation on TFC is conducted and the results indicate that the proposed model is capable of estimating TFC within ±6% of actual value. Phase-wise review on TFC estimation error shows that cruise phase and descent phase fuel consumption could be estimated within ±6% and ±10% of actual value respectively. The scope of the proposed model is expected to be enhanced by applying it as a platform to review aircraft's performance in other applications.

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