**2019 International Conference on Aviation Safety and Information Technology (ICASIT 2019)**

# Fuel Estimation Model of Aircraft Cruise phase Based on Flight Data

Kun Liu
Zhongyu New Technology
China Academy of Civil Aviation Science and Technology
Beijing, China
liukun@zy-cast.com

Shan Jiang
Zhongyu New Technology
China Academy of Civil Aviation Science and Technology
Beijing, China
jiangsh@zy-cast.com

Hui Chen
Zhongyu New Technology
China Academy of Civil Aviation Science and Technology
Beijing, China
chenhui@zy-cast.com

Tielin Wang
Zhongyu New Technology
China Academy of Civil Aviation Science and Technology
Beijing, China
wangtl@zy-cast.com

Xingyun Jiao
Zhongyu New Technology
China Academy of Civil Aviation Science and Technology
Beijing, China
jiaoxy@zy-cast.com

***Abstract*—ABSTRACT: Concerning most existing fuel estimate model methods only consider plane profile, complex calculation and poor engineering application. By extracting the key parameters of fuel consumption in cruise phase by aircraft performance, the model is presented in the Paper. Airborne residual fuel are calculated through the special flight plan and real-time flight data as the input training model. The simulation results show that the precision and engineering application are obviously improved for the nonlinear fuel estimation problem by this algorithm.**

***Keywords—Flight data; Fuel consumption; Fuel estimate; Flight performance***

## I. INTRODUCTION

Due to fuel consumption is directly related to flight safety and economic benefits of the carrier's aircraft, while airlines have strict implementation the relevant fuel requirements of the CCAR121-R5 and is well prepared for the fuel before release. It is especially important to strengthen fuel real-time monitoring and improve flight fuel monitoring procedures. At present, fuel information is mainly based on the ACARS data link, however due to the high price of ACARS, the message frequency is mostly around 10 minutes. The time slot of two messages constitutes the vacuum zone of fuel monitoring, and the establishment of accurate flight fuel consumption estimation model becomes the key of fuel monitoring. key. Establishing an accurate fuel estimation model depends on the flight plan for specific aircraft performance, mission and flight environment, and estimates the airborne residual fuel with real-time flight data.

At present, most of the aircraft fuel consumption estimation models are based on the vertical profile of flight, moreover the parameters of the models need been consulted from aircraft performance, so the calculation is complex and the fuel consumption caused by horizontal motion can not be estimated. BelaP.Collins proposed a fuel estimation model based on the principle of energy conservation, while according to the energy balance between the mechanical energy and fuel consumption in flight, the fuel consumption of the aircraft is calculated[1]. The shortcoming of this method is that the performance parameters are difficult to obtain and the horizontal parameters are not taken into account. Trani AA trained neural networks based on the record database and performance database to obtain fuel consumption values. This method requires high performance data selection, and cannot consider meteorological parameters and horizontal fuel consumption, and the data point collection effect is not good. In addition, the proposed neural network structure Convergence is slow and accuracy is limited[3].

In view of the current problems of accuracy, scope of application, engineering applications, etc., this paper proposes the fuel estimation model of based on real-time flight data and the specific flight plan in cruise phase. Through the processing of the flight plan split micro-element, the key parameters of fuel consumption in different sections of the flight are optimized and extracted. ACARS fuel is used as the initial quantity of the model, and the real-time ACARS fuel is used to dynamically correct the estimated fuel to establish real-time continuous fuel perception for the dispatcher.

## II. INFINITESIMAL RESOLUTION OF FLIGHT PLAN

Flight plan is that the dispatcher collects release information such as flight load, timely weather conditions, minimum executable weather standards for captain, minimum equipment list (MEL), take-off performance, alternate airport and flight announcement before 2 hours or earlier of the departure time. When the above conditions meet the requirements of CCAR121, according to the best height, Mach number and cost index, the data of taxiing, take-off, air fuel consumption and residual fuel on the ground are calculated, and then through the above key fuel information, the take-off weight, fuel-free weight and landing weight are obtained respectively. While checking that the three weights are less than the maximum limit weight of the corresponding aircraft, the flight plan is made. In this paper, fuel consumption is estimated based on the specific flight plan and real-time flight data. In order to monitor fuel consumption of real-time flight more finely and continuously, the flight plan micro-elements are separated[4].

The planned route of flight plan is composed of a series of waypoints $f_1, f_2 \cdots f_i \cdots f_n$ , and the cruise phase consists of the waypoints between TOC and TOD $f_{\text{TOC}} \cdots f_i \cdots f_{TOD}$ and $i \in (1, \text{n})$ , The micro-element processing of planning information for any two adjacent planned waypoints $f_i, f_{i+1}$ ,

$$\text{N=}\frac{f(t_{i+1}) - f(t_i)}{\Delta t} \quad (1)$$

In the equation, N is the number of parts per flight segment, $f_i, f_{i+1}$ is the cumulative flight time of route point $f(t_i)$ , $f(t_{i+1})$ and $\Delta t$ is the time element of split point.

$$f_{\text{i,k}} = \int_{t_{i,k}}^{t_{i,\text{k}+1}} \frac{f_{i+1} - f_i}{f(t_{i+1}) - f(t_i)} dt \quad (2)$$

In the equation, $0 \le k < N$ , $f_{\text{i,k}}$ is the planned airborne residual fuel for each split route point. Since $\Delta t$ is small and the environment of adjacent routes is basically the same, the external static temperature can be considered approximately equal.

## III. FUEL CONSUMPTION ESTIMATION MODEL

In this paper, the parameters of fuel consumption in cruise phase are determined by aircraft performance, and the fuel consumption model is established based on the parameters. The input parameters of the model are selected according to CFP and real-time flight data.

According to the real-time flight status of the aircraft, it is judged that the aircraft is in the cruise phase, the flight distance is dR, and the fuel consumption is dy, and then

$$\text{SR} = \frac{dR}{dy} \quad (3)$$

The SR is the flight range of the aircraft, which represents the distance per unit fuel consumed by the aircraft in flight.

Derivation from (3)

$$dy = \frac{dR}{\text{SR}} \quad (4)$$

According to the relationship between flight distance dR and airspeed $v$ and flight time $dt$ .The relationship between airspeed $v$ and Mach number M is also discussed.

$$dR = vdt = a_0 \sqrt{T / T_0} Mdt \quad (5)$$

Equation $a_0$ is the sound speed under sea level standard atmospheric conditions, T is the atmospheric temperature at the altitude of the aircraft, and $T_0$ is the atmospheric temperature under sea level standard atmospheric conditions.

According to the performance of the aircraft[5],

$$\text{SR=}\frac{1}{\text{sfc}} \cdot \frac{\sqrt{C_L}}{C_D} \cdot \sqrt{\frac{2}{S_w}} \cdot \frac{1}{\sqrt{W}} \cdot \frac{1}{\sqrt{\rho}} \quad (6)$$

Equation sfc is the fuel consumption rate, represents the amount of fuel consumed by the aircraft in generating unit thrust in a unit time, $C_L$ is the lift coefficient, $C_D$ is the drag system, $S_w$ is the wing area, $\rho$ is the weight of the aircraft, t is the atmospheric density of the aircraft's height.

Substitute (5) and (6) into (4)

$$\text{dy=}\frac{\sqrt{W} \cdot \sqrt{\rho} \cdot \text{sfc} \cdot C_D \cdot \sqrt{S_w} \cdot a_0 \sqrt{T} M}{\sqrt{2T_0 \cdot C_L}} dt \quad (7)$$

Equation (7) Integrating time on both sides

$$\text{y=}\int_{t_1}^{t_2} \frac{\sqrt{W} \cdot \sqrt{\rho} \cdot \text{sfc} \cdot C_D \cdot \sqrt{S_w} \cdot a_0 \sqrt{T} M}{\sqrt{2T_0 \cdot C_L}} dt \quad (8)$$

Equation y is the fuel consumption in cruise phase, $\text{t}_1$ is the start time of $\Delta\text{t}$ fuel consumption estimation and $\text{t}_2$ is the end time of $\Delta\text{t}$ fuel consumption estimation.

It should be pointed out that in view of the randomness of the variables in equation (8), it is difficult to integrate them directly, However, it can be known that the key factors of fuel consumption in cruise phase include aircraft weight, atmospheric density, atmospheric temperature, cruise Mach number and cruise time.

Because the $\Delta\text{t}$ time of the model is very short and the atmospheric density and temperature are calculated by a fixed value, the three parameters of aircraft weight, cruise Mach number and cruise time can be obtained from real-time ADS-B flight data and the special flight plan.

According to the performance of the aircraft,

$$\rho \left\langle \begin{array}{ll} \rho_0 \left(1 - 0.0065 \dfrac{H}{T_0}\right)^{4.255888} & , H \le 11000m \\ \rho_{11} e^{-\frac{H-11000}{QT_{11}}} & ,11000m \le H \le 20000m \end{array} \right| \quad (9)$$

Under the standard atmospheric conditions of $\rho_0$ sea level, the atmospheric density is 11000 m in $\rho_{11}$ , the atmospheric temperature is 11000 m in $T_{11}$ , the gas constant is Q, and the flight altitude is H.

The equation (9) shows that atmospheric density $\rho$ is closely related to flight altitude, and flight altitude can be obtained from real-time ADS-B data. Therefore, the atmospheric pressure altitude is selected as the input parameter of the model to reflect the influence of atmospheric density on fuel consumption.

Atmospheric temperature T, also known as atmospheric static temperature, can be obtained by splitting the external static temperature T in flight planning points. Therefore, the external static temperature can be used as the input parameter of the model to reflect the influence of atmospheric temperature on fuel consumption.

Aircraft weight also varies with fuel consumption. Aircraft weight can be obtained according to the aircraft dry weight in flight plan. Therefore, the aircraft dry weight is selected as the input parameter of the model to reflect the impact of aircraft weight on fuel consumption in cruise phase.

In summary, the input parameters of the model are dry weight, air pressure height, flight time, external static temperature and cruise Mach number.

Based on the above model, the current airborne residual fuel can be obtained.

$$Y = F(dy) - \int_{t_1}^{t_2} \frac{\sqrt{W} \cdot \sqrt{\rho} \cdot \mathrm{sfc} \cdot C_D \cdot \sqrt{S_w} \cdot a_0 \sqrt{T} M}{\sqrt{2T_0 \cdot C_L}} dt \quad (10)$$

Equation Y represents the current airborne residual fuel and $F(dy)$ represents airborne residual fuel of the time $t_1$.

## IV. EXPERIMENTAL RESULTS AND ANALYSIS

Based on the fuel consumption model, the domestic route from Shanghai Pudong International Airport to Nanning Wuxu International Airport (PVG-NNG) is selected. According to the fixed time interval, the flight plan and real-time ADS-B data are input into the model based on the ACAS message, intercepting the results of a certain period of time as follows table I.

TABLE I THE RESULTS OF A CERTAIN PERIOD OF TIME

| ACARS Time | ACARS Fuel/kg | Estimated Time | Estimated Fuel/kg |
|---|---|---|---|
| 7:18 | 11974 | 7:20 | 11974 |
| 7:21 | 12265 | 7:21 | 12265 |
| 7:21 | 12265 | 7:21 | 12256 |
| 7:21 | 12265 | 7:22 | 12164 |
| 7:21 | 12265 | 7:23 | 12093 |
| 7:21 | 12265 | 7:24 | 12022 |
| 7:21 | 12265 | 7:25 | 11951 |
| 7:21 | 12265 | 7:26 | 11880 |
| 7:21 | 12265 | 7:27 | 11809 |
| 7:21 | 12265 | 7:28 | 11738 |
| 7:21 | 12265 | 7:29 | 11652 |
| 7:21 | 12265 | 7:30 | 11565 |
| 7:21 | 12265 | 7:31 | 11479 |
| 7:21 | 12265 | 7:32 | 11393 |
| 7:21 | 12265 | 7:33 | 11307 |
| 7:21 | 12265 | 7:34 | 11229 |
| 7:21 | 12265 | 7:35 | 11151 |
| 7:21 | 12265 | 7:36 | 11072 |
| 7:36 | 10614 | 7:36 | 10614 |

The fuel profile of the whole route is shown below Fig.1

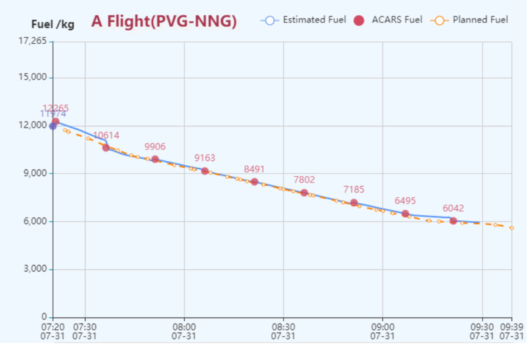

Fig. 1. The Fuel Profile of the Whole Route

From the results of the above chart, it can be seen that the difference between the estimated fuel based on the model and ACARS fuel message in adjacent time is small, and the fitting degree between the estimated fuel curve and the flight plan fuel consumption curve of the whole flight route is high.

In this paper, 300 domestic routes and 300 international routes are selected in the sample space. Statistical analysis of the unit average deviation between the estimated fuel consumption in each cruise phase and that in the latest ACARS message.

$$\Delta_i = \mathrm{abs}\left(\frac{f_e - f_{acars}}{t_e - t_{acars}}\right) \Delta t \quad (11)$$

In the Equation, $\Delta_i$ denotes the deviation between the estimated value and the actual message, $f_e$ denotes the estimated fuel consumption, $t_e$ denotes the estimated fuel consumption time, $f_{acars}$ denotes the fuel consumption of ACARS message, $t_{acars}$ denotes the time of the fuel consumption of ACARS message.

$$\mu = \mathrm{E}(\Delta_1, \Delta_1 \cdots \Delta_i \cdots \Delta_n) \quad (12)$$

In the Equation $\mathrm{i} \in (1, 300)$, $\mu$ is the average deviation of each route.

Among them, there are 300 valid sample points for domestic routes and 300 valid sample points for international routes. Fig. 2 The deviation between the estimated value of international routes and the actual fuel consumption, and the deviation between the estimated value of Fig. 3 domestic routes and the actual fuel consumption. In order to characterize the quality of fuel consumption estimation more intuitively, the deviation values are normalized based on min-max Fig.4 and Fig. 5 are the normalized results of fuel consumption prediction corresponding to domestic and international routes, respectively.

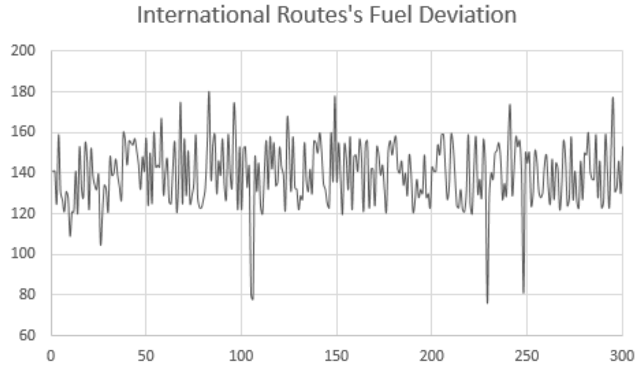

Fig. 2. Deviation Value of Fuel Consumption Estimation for International routes

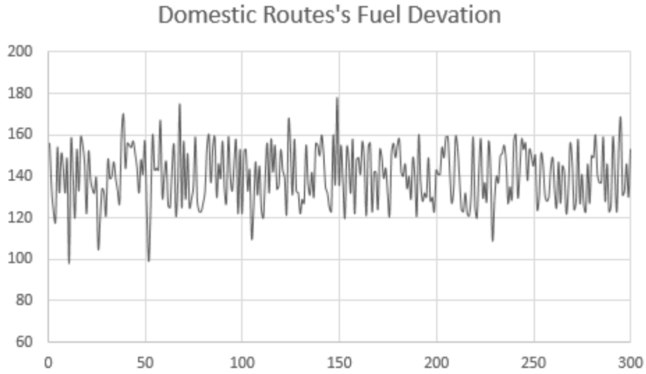

Fig. 3. Deviation Value of Fuel Consumption Estimation for Domestic routes

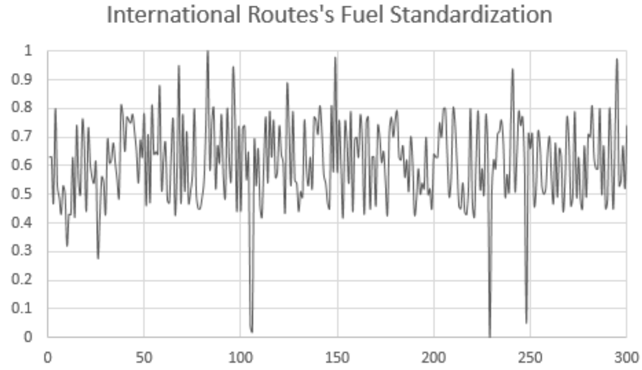

Fig. 4. Standardization of Fuel Volume Deviation Value for International routes

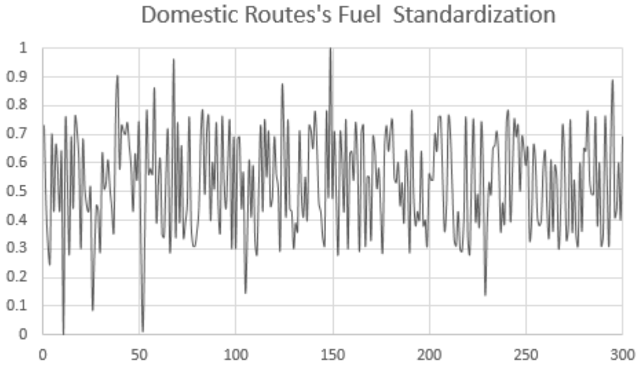

Fig. 5. Standardization of Deviation Value of Domestic Route Fuel Volume

From the forecasting results, the mean value of domestic and international routes predicted in this paper fluctuates little, and the deviation mean value of domestic and international routes is basically the same. The experimental results show that the scheme is applicable to both international and domestic routes, has good forecasting effect and broad engineering application prospects.

## ACKNOWLEDGMENT

By extracting the key parameters of fuel consumption in cruise phase by aircraft performance, the model is presented in the Paper. Airborne residual fuel are calculated through the special flight plan and real-time flight data as the input training model . The simulation results of domestic and international routes show that the precision and engineering application are obviously improved for the nonlinear fuel estimation problem by this algorithm.

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