Aircraft Departure Fuel Consumption Improvement Model Based On Flight Data

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Abstract: Accurate assessment of aircraft fuel consumption is an important means for airlines to reduce flight costs and control fuel emissions. By analyzing the actual flight data of QAR, the functional relationship between the aerodynamic parameters in the fuel consumption model of the departure climb phase is fitted, and the crosswind is added to the fuel consumption assessment model. Based on the analysis of the departure training of Qingdao Airport, the fuel consumption model of the exit climbing stage was calculated using the improved fuel consumption model. The results showed that the calculation accuracy of the wind tunnel experiment was improved by 3.6%, and the theory of the fuel evaluation experiment considering the crosswind was considered. The accuracy of the model calculation and QAR data is 93.3%.

1. Introduction
With the continuous rapid growth of air traffic, air traffic volume will be doubled in the next 15 years (Airbus, 2015). A report from the International Air Transport Association in 2017 stated that aircraft fuel oil consumption is the operating cost expenditure that accounts for the largest proportion in airlines (IATA, 2017). Terminal airspace is the air traffic hub, and the contradiction between the limitation of fuel oil emission and the rapid growth of traffic volume becomes increasingly prominent. Therefore, establishing an evaluation model for departure fuel oil consumption in practical operation and accurately controlling fuel oil-loading quantity are important to improve the operating benefits of airlines and reduce fuel oil emission in terminal areas.

Analysis of many influence factors of fuel oil consumption. Scholars (Turgut et al., 2014; Brueckner and Abreu, 2017) determined that aircraft mass and speed during the flight process at cruising altitude were the main influence factors of fuel oil consumption; however, the modeling calculation of fuel oil consumption was not involved. Nikoleris et al. (2011) and Singh and Sharma (2015) classified and evaluated estimation methods for aircraft oil consumption from macroscopic aspects based on the estimation of total fuel oil consumption.

Calculation of fuel oil consumption on the basis of the BADA aircraft performance model. The BADA Aircraft Performance Model (APM) is developed and maintained by EUROCONTROL (EEC, 2009). Many scholars have studied aircraft fuel oil consumption models based on APM in the BADA database. Burzlaff (2017) and Pagoni and Psaraki-Kalouptsidi (2017) calculated fuel oil consumption during aircraft flight process on the basis of a fuel oil consumption model in the BADA database;
however, relations among aerodynamic parameters were acquired by static diagrams obtained through a wind tunnel experiment in this study. Relational data of static diagrams were all test flight data with which true flight data had certain gaps, which resulted in errors in calculated results.

*Prediction of fuel oil consumption based on regression analysis.* Yanto and Liem (2018) integrated the trajectory simulation results of the state-of-the-art BADA into a fuel burn model to obtain an effective and accurate computing method of fuel consumption. Aircraft effective load was taken as the input in the linear regression model, the fuel combustion model was used to generate a fuel combustion database, and an accurate simulation model of fuel consumption was obtained through data integration.

To sum up, all prediction methods for fuel oil consumption have their respective deficiencies. The modeling method based on the principle of energy conservation does not consider horizontal plane factors in the climbing phase or meteorological factors, such as crosswind. The training model based on neural network presents an obvious fluctuation in the prediction result, a certain error exists between estimated total oil consumption and true value, and the influences of performance parameters on fuel oil consumption is not analyzed. The linear regression method has high requirements for true data, and the present literature has not involved meteorological factors or performance parameters; consequently, the prediction accuracy is degraded. Most of the present studies on fuel oil consumption in the climbing phase have considered the influence of fuel oil consumption in the conventional climbing phase, few have considered the influence of CCO on fuel oil consumption, and the two are not compared yet. Actual aerodynamic parameters are not constant values. If set as constant values, they will result in erroneous computed results.

On the basis of the above considerations, the present study aims to use true QAR operation data to optimize aerodynamic parameters and integrate crosswind kinetic model into BADA fuel oil consumption model. Innovative points of this study are as follows.

- Aerodynamic parameters can be obtained only by referring to the static diagram relation acquired through a wind tunnel experiment. Therefore, the additional oil consumption caused by aircraft performance degradation cannot be estimated, which will result in errors between the computed result and actual oil consumption. The relation between lift and resistance coefficients in the BADA fuel oil consumption model is obtained on the basis of QAR data fitting method, and an optimization model for fuel oil consumption under wind-free conditions is determined.
- Previous studies of fuel oil consumption models have scarcely involved the influence of crosswind on fuel oil consumption; thus, computed results are inaccurate. Crosswind parameter is added to the optimization model of fuel oil consumption through a flight kinetic analysis in the departure climbing phase, which guarantees the computing accuracy of fuel oil consumption.

The remainder of this paper is organized as follows. Section 2 introduces an aircraft fuel oil consumption model and aerodynamic and thrust models. An optimization model for fuel oil consumption is obtained on the basis of the optimization of aerodynamic parameters and the analysis of the influence of crosswind on flight ground speed in Section 3. Two comparative experiments with A320 aircraft as an example are established in Section 4. Section 5 consists of the study conclusions and expectations.

2. BADA-based fuel oil consumption model

The BADA aircraft performance database model (EEC, 2009; EEC, 2011), which is a model developed by EUROCONTROL for flight kinematic analysis, is mainly applied to flight simulation, flight trajectory prediction, emission evaluation, and oil consumption calculation; it exhibits great advantages in the aspects of flight simulation degree, complexity, and accuracy. The aircraft fuel oil consumption model in the climbing phase is expressed as follows.

**Parameters:**
- $\eta$: thrust-specific fuel flow, kg/(min·kN);
- $V_{TAS}$: true airspeed, knots;
- $C_{f1}$: first thrust-specific fuel consumption coefficient, kg/(min·kN);
The fuel oil consumption of the unit thrust of a turbo jet aircraft within unit time is

\[ f_{\text{climb}} = \frac{C_f}{2} \left( V_{\text{AS}} \right) \eta + \frac{V_{\text{AS}}}{C_f} \]  

Through a combination with the thrust in the nominal flight section in the aircraft-climbing phase, the fuel oil consumption within unit time can be derived as follows:

\[ f_{\text{climb}} = \eta T \]  

(2) Aerodynamic and thrust models

The aircraft will bear the effects of lifting force, gravity, resistance, and thrust in the flight, which will directly affect its flight speed. On the basis of stress-bearing analysis and aerodynamic performance data in the climbing phase, resistance and thrust models can be obtained as follows:

\[ T = D + m g \sin \gamma + m \frac{dV_{\text{AS}}}{dt} \]  

\[ D = \frac{1}{2} \rho SV_{\text{AS}}^2 C_D \]  

\[ L = \frac{1}{2} \rho SV_{\text{AS}}^2 C_L = mg \cos \gamma \]  

The fuel oil consumptions at different times in the climbing phase can be obtained through the above two groups of models. If the time interval of climbing can be equally divided into \( k \) time slices, then the fuel oil consumption in the entire climbing phase can be obtained through superposition, as
shown as follows:

\[ F = N \sum_{i=1}^{k} f_{\text{climb}}. \]  

(6)

3. Optimization model of fuel oil consumption

The fuel oil consumption model in the climbing phase based on the BADA database is optimized in this section in the aspects of (1) aerodynamic parameters and (2) crosswind influence.

3.1 Optimization of aerodynamic parameters

On the basis of actual QAR operation data, the functional fitting method of true data is used to obtain the relation between resistance coefficient and lifting force. A320 model is taken as an example. Multigroup QAR data of the A320 model in an airline are initially acquired, and the corresponding multigroup resistance coefficients and lifting force data under the same Mach number (for example, the Mach Number is 0.7) are then extracted. (see the Appendix)

The optimal fitting results of power, exponential, and polynomial functions are determined through goodness of fit (R²) and the sum of squared errors of prediction (SSE). The closer the R² value is to 1, the better the fitting degree of the observed value; the residual sum of squares is a statistical index used to reflect the closeness degree of relations among variables; the smaller the value is, the more accurate the fitting result is. Fitting relations that correspond to other Mach numbers are acquired through the same method. The accurate approximate resistance coefficient is obtained through the lift coefficient solved through Formula (5), as well as the fitting relation between resistance and lift coefficients.

3.2 Calculation of fuel oil consumption under crosswind

Flight environment, especially crosswind, exerts a major influence on fuel oil consumption, and the crosswind influence on the aircraft changes with geographical position and flight altitude \( H \). The influence of 3D wind on flight ground speed is considered in this section to establish a calculation model of fuel oil consumption under the influence of 3D wind. The wind speed and direction are denoted as \( V_{\text{wind}} \) and \( D_{\text{wind}} \), respectively, in which the wind direction is \( 0° \) in the true north direction and is positive in the clockwise direction. Wind data at different altitudes in different areas can be acquired through an inquiry of meteorological data, including wind speed and direction.

To study the influence of 3D wind on aircraft flight, the projection vector \( [u_{wg} \ v_{wg} \ w_{wg}]^T \) of wind speed in the ground coordinate system can be calculated according to wind speed \( V_{\text{wind}} \) and direction \( D_{\text{wind}} \), that is,

\[ u_{wg} = V_{\text{wind}} \cos D_{\text{wind}}; \]

(7)

\[ v_{wg} = V_{\text{wind}} \sin D_{\text{wind}}; \]

(8)

\[ w_{wg} = 0. \]  

(9)

The projection vector \( V_{GS} \) of flight ground speed \( [u \ v \ w]^T \) in the body coordinate system under the crosswind condition is

\[
V_{GS} = \begin{bmatrix} u \\ v \\ w \end{bmatrix} = L_{sb} \begin{bmatrix} V_{TAS} \\ 0 \\ 0 \end{bmatrix} - L_{bg} \begin{bmatrix} u_{wg} \\ v_{wg} \\ w_{wg} \end{bmatrix} \\
\begin{bmatrix} \cos \theta \cdot V_{TAS} - \cos \theta \cdot \cos \phi \cdot u_{wg} - \cos \theta \cdot \sin \phi \cdot v_{wg} + \sin \theta \cdot w_{wg} \\ \sin \theta \cdot V_{TAS} - (\sin \theta \sin \phi \sin \phi + \cos \phi \cos \phi) u_{wg} - (\sin \theta \sin \phi \sin \phi + \cos \phi \cos \phi) v_{wg} - \sin \phi \cos \theta \cdot w_{wg} \\ - (\sin \theta \cos \phi \cos \phi + \sin \phi \sin \phi - \sin \phi \cos \phi) u_{wg} - (\sin \theta \cos \phi \sin \phi) v_{wg} - (\cos \phi \cos \theta) w_{wg} \end{bmatrix}. \]  

(10)
where $L_{nk}$ and $L_{nq}$ are respectively calculated as follows:

$$L_{nk} = \begin{bmatrix} \cos \phi \cos \theta & -\cos \phi \sin \theta \cos \varphi + \sin \phi \sin \varphi & -\cos \phi \sin \theta \sin \varphi - \sin \phi \cos \varphi \\ \sin \theta & \cos \theta \cos \phi & \cos \theta \sin \varphi \\ \sin \cos \theta & -\sin \phi \cos \theta \cos \varphi \cos \sin \phi \sin \varphi \cos \sin \theta \sin \cos \varphi + \cos \phi \cos \varphi \end{bmatrix}; \quad (11)$$

$$L_{nq} = \begin{bmatrix} \cos \theta \cos \varphi & \sin \theta \sin \varphi & -\sin \theta \\ \sin \theta \sin \cos \theta \cos \varphi \cos \sin \phi \sin \cos \theta \sin \sin \phi \cos \sin \theta \sin \cos \varphi + \cos \phi \cos \varphi \\ \sin \theta \sin \cos \theta \cos \varphi \cos \sin \phi \sin \varphi \sin \cos \phi \cos \sin \theta \sin \cos \varphi + \cos \phi \cos \varphi \\ \sin \theta \sin \cos \theta \cos \varphi \cos \sin \phi \sin \varphi \sin \cos \phi \cos \sin \theta \sin \cos \varphi + \cos \phi \cos \varphi \end{bmatrix}. \quad (12)$$

$[u_{wg} \ v_{wg} \ w_{wg}]^T$ is calculated according to Formulas (10)–(12). That is, the aircraft ground speed is

$$V_{gs} = \sqrt{u^2 + v^2 + w^2}.$$

Computational formulas of resistance and thrust under the crosswind condition can be obtained according to Formulas (3) and (4) as shown as follows:

$$D = \frac{1}{2} \rho S V_{gs}^2 C_D = \frac{1}{2} \rho S C_D (u^2 + v^2 + w^2); \quad (13)$$

$$T = \frac{1}{2} \rho S C_D (u^2 + v^2 + w^2) + mg \sin \gamma + m \frac{dV_{TAS}}{dt}. \quad (14)$$

Fuel oil consumption under the crosswind condition can be calculated according to Formulas (1), (2), and (6), as shown as follows:

$$f_{climb} = \eta_T = C_f \left(1 + \frac{V_{TAS}}{C_{f2}}\right) \left[\frac{1}{2} \rho S C_D (u^2 + v^2 + w^2) + mg \sin \gamma + m \frac{dV_{TAS}}{dt}\right]; \quad (15)$$

$$F = N \sum_{i=1}^{N} f_{climb} = \sum_{i=1}^{N} \left[\frac{1}{2} \rho S C_D (u^2 + v^2 + w^2) + mg \sin \gamma + m \frac{dV_{TAS}}{dt}\right]. \quad (16)$$

4. Numerical case study

The departure of Qingdao Liuting International Airport (ICAO: ZSQD) was mainly taken as the study object, and the departure of Taiyuan Wusu International Airport (ICAO: ZBYN) was added for model verification. Actual QAR departure operation data of A320 aircraft model in Liuting International Airport were obtained. On the basis of the compilation of departure flight trajectory simulation procedures in Qingdao, the above theoretical models were combined to establish five comparative experiments. A data analysis of comparative experiments verified that the theoretical model proposed in this study is superior to the past evaluation models for fuel oil consumption. The influences of different aircraft masses and climbing angles on fuel oil consumption were analyzed.

4.1 Data acquisition and preparation

Through simulated programming and combining waypoint information, aircraft flight trajectory was simulated, parameters in the simulated flight trajectory were substituted into the fuel oil consumption model, and a theoretical calculation of fuel oil consumption was conducted.

The airport reference point of Qingdao Liuting International Airport was taken as the origin of the rectangular coordinate system to simulate flight trajectory in the departure climbing phase. The simulated trajectory and actual QAR flight trajectory are shown in Fig. 1.
The simulated flight trajectory information and Formula (5) can be combined to solve the lift coefficients of all points in the flight trajectory. The resistance coefficient of each point can be solved through the relation between lift and resistance coefficients. The resistance can be solved according to Formula (4), where air density $\rho$, temperature $T_1$, and air pressure intensity $p_a$ are all obtained through the formulas that show changes in meteorological parameters with flight altitude in Section 2. The thrust value was solved according to Formula (3). The fuel oil consumption at each point in the flight trajectory was solved by combining Formulas (1) and (2).

4.2 Two comparative experiments

This calculating example was the departure of Qingdao Liuting International Airport, the aircraft fuel oil consumption in the climbing phase was discussed, and two comparative experiments were performed as follows. (1) For the Airbus A320 aircraft model (Airbus, 2016), experimental comparison method was used to verify the optimization of aerodynamic parameters in the model, such that the model could become accurate. (2) Crosswind was added on the basis of the optimization of aerodynamic parameters, such that the model could become accurate, and the theoretical value of fuel oil consumption calculated through the optimization model was compared with the actual flight QAR data of one airline to verify whether the optimized fuel oil consumption model was feasible.

Experiment 1: optimization experiment of aerodynamic parameters

In fuel oil consumption models proposed by relevant scholars (Singh and Sharma, 2015; Senzig et al., 2015), aerodynamic parameters are obtained usually by referring to the static diagram relation acquired through a wind tunnel experiment. The data of this method are derived from ideal data.

The following experiment was hereby designed to conduct a comparative analysis of past methods with the fitting method of actual QAR data proposed in this study. (1) On the basis of the BADA-based fuel oil consumption model in the climbing phase, resistance and lift coefficients among aerodynamic parameters were acquired through the static diagram relation obtained by a wind tunnel experiment. Points were taken and added in the model to calculate fuel oil consumption. (2) Resistance and lift coefficients among aerodynamic parameters were obtained through the relation fitted using the QAR data-based least squares method proposed in this study, and they were added to the model to calculate fuel oil consumption.

The above experimental calculated results were compared with QAR data. The relations of the aerodynamic parameters fitted using the QAR data-based least squares method were more accurate than those obtained by referring to the static diagram relation acquired through a wind tunnel experiment.

Least squares method was used for polynomial fitting by combining QAR data and Origin
software. According to Section 2, multigroup resistance and lift coefficients that correspond to different Mach numbers were acquired. A Mach number of 0.7 was taken as an example in this study, and the relations of resistance and lift coefficients were fitted. The fitting relations that correspond to other Mach numbers were acquired through the same method. Lift and resistance coefficients that correspond to 0.7 Mach number were selected among QAR data of A320 aircraft and imported into Origin software. A curve fitting function was used to fit power function, exponential function, linear function and quadratic Function, and linear function and cubic function. The fitting results are summarized in Table 1.

### Table 1 Summary Sheet of Fitting Results

| Function type     | Expression of fitting function | Goodness of fit | Residual sum of squares |
|-------------------|--------------------------------|-----------------|-------------------------|
| Power function    | \( f(x) = 0.0488 \times x^{0.6795} \) | 0.9674          | 2.827 \times 10^{-5}   |
| Exponential function | \( f(x) = 0.0153 \times 1.35^x \) | 0.9919          | 6.99 \times 10^{-6}    |
| Polynomial function (linear function) | \( f(x) = 0.0410x + 0.0098 \) | 0.9771          | 1.982 \times 10^{-5}   |
| Polynomial function (quadratic function) | \( f(x) = 0.0680x^2 - 0.0287x + 0.0270 \) | 1               | 2.629 \times 10^{-8}   |
| Polynomial function (cubic function) | \( f(x) = 0.01302x^3 + 0.04804x^2 - 0.01872x + 0.02538 \) | 1               | 2.037 \times 10^{-8}   |

The fitting expressions, goodness-of-fit values, and SSEs of all function types can be obtained on the basis of the results in Table 1. As stated in Section 3, SSE and \( R^2 \) are statistical indexes that reflect the closeness degree of relations among variables; the smaller the SSE value is, the closer the goodness-of-fit value is to 1, and the more accurate the fitting result will be. In Table 4, the SSEs of quadratic and cubic functions among polynomial functions are smaller than those of power, exponential, and linear functions; that is, the fitting precisions of quadratic and cubic functions in the judgment index, namely, goodness of fit, are higher than those of other three types of fitting functions. The goodness-of-fit values of quadratic and cubic functions are both 1, that of power function is 0.9674, that of exponential function is 0.9919, and that of linear function is 0.9771. A comparison indicates that the fitting precisions of quadratic and cubic functions in the judgment index, namely, goodness of fit, are higher than those of other fitting function types. Two judgment criteria, goodness of fit and SSE, were combined, and both quadratic and cubic functions could be taken as relational expressions of data points.

Fitting of polynomials with degrees being greater than 3 was also studied. Goodness-of-fit values are all 1, and their SSE values are approximate to (slightly smaller than) those of quadratic and cubic polynomials. However, if the degree is extremely high, then the curve will be forced to pass through the sample point and truthfulness will be lost, which will easily generate Runge’s phenomenon and high-frequency vibration. High-degree polynomial functions were neglected in this study, whereas quadratic function was used as a fitting relational expression of data points. Therefore, the fitting relational expression that corresponds to 0.7 Mach number is

\[
y = 0.0680x^2 - 0.0287x + 0.0270 .
\]  

(17)

The relational expression between resistance and lift coefficients under different Mach numbers can be fitted through the same method, as shown in Table 2.
Table 2 Fitting Relational Expression

| Mach number (z) | Fitting relational expression (y is the resistance coefficient, and x is the lift coefficient) |
|-----------------|------------------------------------------------------------------------------------------------|
| 0.2             | \( y = 0.0606x^2 - 0.0232x + 0.0271 \)                                                    |
| 0.3             | \( y = 0.0621x^2 - 0.024x + 0.0271 \)                                                   |
| 0.4             | \( y = 0.0636x^2 - 0.0254x + 0.0270 \)                                                  |
| 0.5             | \( y = 0.0651x^2 - 0.0265x + 0.0270 \)                                                  |
| 0.6             | \( y = 0.0666x^2 - 0.0276x + 0.0270 \)                                                  |
| 0.7             | \( y = 0.0681x^2 - 0.0287x + 0.0270 \)                                                  |

The above relational expressions were used to acquire relational expression among Mach number, resistance coefficient, and lift coefficient using interpolation method as follows:

\[
Z = \frac{0.01676x^2 - 0.0067x + 0.0127}{y}. \quad (18)
\]

The relational image among the three is shown in Fig. 2.

![3D Relational Graph](image)

Fig. 2 3D Relational Graph among the Mach Number, Resistance Coefficient, and Lift Coefficient of Airbus A320

The resistance and lift coefficients acquired through the fitting result and the wind tunnel experiment were respectively substituted into the fuel oil consumption model for the calculation. Each 72 s was taken as a flight phase during the 720 s flight process, 10 flight phases were divided, and the fuel oil consumption in each phase was calculated, as presented in Table 3.

Table 3 Comparison Chart of Fuel Oil Consumption in 10 Flight Phases (Unit: kg)

| Flight phase | Fuel oil consumption based on the wind tunnel experiment | Fuel oil consumption based on the fitting method | QAR actual data | Calculation accuracy based on the wind tunnel experiment (%) | Calculation accuracy based on the fitting method (%) |
|--------------|----------------------------------------------------------|-----------------------------------------------|----------------|----------------------------------------------------------|--------------------------------------------------|
| A            | 81.8                                                     | 85.8                                         | 98             | 83.47                                                    | 87.55                                            |
| B            | 93.5                                                     | 97.6                                         | 109            | 85.78                                                    | 89.54                                            |
| C            | 79.6                                                     | 85.9                                         | 96             | 82.92                                                    | 89.48                                            |
| D            | 84.3                                                     | 90.2                                         | 100            | 84.30                                                    | 90.20                                            |
| E            | 108.4                                                    | 115.3                                        | 126            | 86.03                                                    | 91.51                                            |
| F            | 107.2                                                    | 112.8                                        | 126            | 85.08                                                    | 89.52                                            |
| G            | 106.5                                                    | 110.6                                        | 124            | 85.89                                                    | 89.19                                            |
| H            | 107.1                                                    | 111.2                                        | 119            | 90                                                        | 93.45                                            |
| I            | 101.1                                                    | 105                                          | 112            | 90.27                                                    | 93.75                                            |
| J            | 95.7                                                     | 100.1                                        | 106            | 90.28                                                    | 94.43                                            |
A quantitative analysis of Table 6 shows that all fuel oil consumptions calculated through the wind tunnel experiment in each flight phase are smaller than the fuel oil consumption calculated through the fitting method and QAR data. This result was due to the fact that the static diagram relation was acquired through a wind tunnel experiment under ideal circumstances and test flight data were used to obtain their relation; however, the additional oil consumption caused by aircraft performance degradation was not considered. The calculation accuracy of fuel oil consumption using the wind tunnel experiment is $965.2/1,116 \times 100\% = 86.5\%$, and the calculation accuracy through the fitting method is $1,014.5/1,116 \times 100\% = 90.9\%$. A comparison of the calculation accuracies of fuel oil consumption shows that the relational expressions of aerodynamic parameters obtained through polynomial fitting using the QAR data-based least squares method are more accurate than those given by the wind tunnel experiment; hence, the calculation model of fuel oil consumption is further optimized.

**Experiment 2: analysis of fuel oil consumptions under crosswind condition**

In actual operation, crosswind can exert a major influence on aircraft flight trajectory (Gonzalez-Arribas et al., 2016; Zheng and Zhao, 2011) and directly affects departure fuel oil consumption. Therefore, on the basis of the optimization of aerodynamic parameters, the influence of crosswind on fuel oil consumption was added, crosswind data in QAR data were integrated into the model for theoretical calculation and compared with fuel oil consumption in QAR, and the accuracy of the proposed optimization model of fuel oil consumption was calculated to verify its feasibility. The influence of 3D wind on fuel oil consumption has already been analyzed in the previous theoretical section. Pitch angle $\theta$, yaw angle $\phi$, wind speed $V_{wind}$, and wind direction $D_{wind}$ among QAR data were substituted into Formula (10); ground speed $V_{GS}$ under 3D wind condition was calculated; and ground speed was added to the fuel oil consumption model to obtain fuel oil consumption results at all points. One flight phase during the 720 s flight process constituted 72 s; this flight process was divided into 10 flight phases, and the fuel oil consumption values of all phases were calculated to obtain Table 4.

| Flight phase | A | B | C | D | E | F | G | H | I | J | Total fuel oil consumption |
|--------------|---|---|---|---|---|---|---|---|---|---|-----------------------------|
| Theoretically calculated value | 89 | 102.2 | 88.7 | 93.6 | 118.1 | 115.9 | 113.4 | 113.5 | 107 | 100.2 | 1,041.6 |
| QAR data | 98 | 109 | 96 | 100 | 126 | 126 | 124 | 119 | 112 | 106 | 1,116 |
| Accuracy of each flight phase | 91% | 93.8% | 92.4% | 93.6% | 93.7% | 92% | 91.5% | 95.4% | 95.5% | 94.5% | 93.3% |

This experiment considered crosswind influence based on fitting polynomials; therefore, the fuel oil consumption model in this experiment was a finally optimized model. The calculated results through this model were compared with QAR data to determine the feasibility of the model. Total fuel oil consumption in the entire climbing phase could be obtained as 1,041.6 kg by adding the fuel oil consumptions of all points, and the total fuel oil consumption in the entire climbing phase in QAR data is 1,116 kg; that is, the total accuracy of the fuel oil consumption model could be obtained as $(1,041.6/1,116) \times 100\% = 93.3\%$. The accuracy calculation results of all flight phases are shown in Table 7, which indicate that the proposed optimized fuel oil consumption model has high calculation accuracy in all flight phases; accordingly, the model is feasible.

After the crosswind influence was added, the ground speed would change, thereby resulting in changes in resistance and thrust. Thus, the accuracy increases by $93.3\% - 90.9\% = 2.4\%$ compared with the fuel oil consumption calculated by only using the fitting method. The fuel oil consumption was
changed according to Formulas (2) and (6). As a result, the aircraft fuel oil consumption is close to the fuel oil consumption under the real environment, and the calculation result is accurate.

4.3 Result of the comparative experiments

In the optimization experiment of aerodynamic parameters, on the basis of the power, exponential, and polynomial functions according to the relational curve trend between resistance and lift coefficients in QAR data were taken as fitting functions. The optimal fitting function was finally determined as a quadratic function (Formula (18)) through two parameters, namely, goodness of fit ($R^2$) and SSE, which were used to assess the fitting results. The fitting result was substituted into the fuel oil consumption model. The theoretical calculation result of fuel oil consumption is 1,014.5 kg, and the accuracy is 90.9% compared with QAR data. The theoretical calculation result of fuel oil consumption using the static diagram relation acquired through the wind tunnel experiment is 965.2 kg, and the accuracy is 86.5% compared with QAR data. The actual fuel oil consumption in QAR data is 1,116 kg. The calculated data imply that the fitting method in the fuel oil consumption model is more accurate than the wind tunnel experimental method in obtaining the relations among aerodynamic parameters.

On the basis of the optimization of aerodynamic parameters, the crosswind influence on the fuel oil consumption model was added, and wind data in QAR data were integrated into the model for a theoretical calculation. The theoretical calculation result of fuel oil consumption is 1,041.6 kg, and the accuracy is 93.3% compared with QAR data; therefore, the model is feasible. In comparison with the fuel oil consumption calculated using the fitting method, the accuracy increases by 2.4% because adding crosswind influence in the fuel oil consumption model agrees with actual flight environment. The model is thus optimized, and the accuracy of the calculated result is higher.

5. Conclusion

Global aviation oil presents a sustainable increasing trend, and the proportion of fuel oil cost stays at a high level in civil air transportation cost, which seriously affects the survival and development of airlines. The estimation model of aircraft departure fuel oil consumption established in this study can accurately control fuel oil loading quantity to avoid the oil firing oil phenomenon caused by excessive fuel loading quantity and reduce fuel oil cost.

This study provides estimates of fuel oil consumption in aircraft departure based on an analysis of flight data. This method based on QAR data fitting can accurately obtain the quantitative relations among aerodynamic parameters. The crosswind kinematical model and the functional relations of aerodynamic parameters acquired through fitting were combined to correct the fuel oil consumption model. The improved model was adopted to performed two comparative experiments. A comparison with actual QAR operation data verified that the accuracy of the fuel oil consumption model proposed in this study was improved by 4.4% compared with that of the traditional fuel oil consumption model. Only the influence of meteorological factor, namely, crosswind, on fuel oil consumption was studied; the influences of severe weather conditions, such as low-altitude wind shear, thunderstorm-caused heavy rainfall, atmospheric turbulence, and aircraft ice accretion, on fuel oil consumption were not involved. Therefore, further study should be conducted to discuss the optimal safe aircraft climbing gradients of different aircraft models in terms of saving fuel oil consumption according to weather factors in the airport.

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Appendix

QAR data of A320

| Mach=0.2 | Mach=0.3 | Mach=0.4 | Mach=0.5 | Mach=0.6 | Mach=0.7 |
|----------|----------|----------|----------|----------|----------|
| CL       | CD       | CL       | CD       | CL       | CD       |
| 0.83585  | 0.05171  | 0.82758  | 0.04871  | 0.78957  | 0.04660  |
| 0.84643  | 0.05082  | 0.82207  | 0.04842  | 0.78331  | 0.04615  |
| 0.83079  | 0.05022  | 0.81712  | 0.04734  | 0.77183  | 0.04495  |
| 0.83013  | 0.04954  | 0.80952  | 0.04719  | 0.76196  | 0.04458  |
| 0.82119  | 0.04886  | 0.80355  | 0.04685  | 0.75309  | 0.04418  |
| 0.81955  | 0.04831  | 0.79477  | 0.04647  | 0.74203  | 0.04378  |
| 0.80803  | 0.04793  | 0.78919  | 0.04605  | 0.73236  | 0.04338  |
| 0.80334  | 0.04751  | 0.78561  | 0.04564  | 0.72549  | 0.04303  |
| 0.79775  | 0.04710  | 0.78033  | 0.04523  | 0.71262  | 0.04273  |
| 0.79216  | 0.04669  | 0.77725  | 0.04483  | 0.70675  | 0.04243  |
| 0.78097  | 0.04589  | 0.76866  | 0.04437  | 0.69888  | 0.03982  |
| 0.76979  | 0.04510  | 0.75628  | 0.04384  | 0.68501  | 0.03946  |
| 0.75864  | 0.04432  | 0.74573  | 0.04313  | 0.67414  | 0.03900  |
| 0.74741  | 0.04356  | 0.73111  | 0.04224  | 0.66327  | 0.03851  |
| 0.73621  | 0.04281  | 0.72452  | 0.04174  | 0.64739  | 0.03723  |
| 0.72784  | 0.04226  | 0.71893  | 0.04144  | 0.64152  | 0.03690  |
| 0.72177  | 0.04187  | 0.71514  | 0.04091  | 0.63565  | 0.03646  |
| 0.71413  | 0.04138  | 0.70725  | 0.04035  | 0.62177  | 0.03581  |
| 0.70648  | 0.04090  | 0.69216  | 0.03961  | 0.60389  | 0.03539  |
| 0.69883  | 0.04043  | 0.68097  | 0.03885  | 0.60002  | 0.03509  |
| 0.69118  | 0.03996  | 0.66979  | 0.03810  | 0.59214  | 0.03428  |
| 0.68333  | 0.03950  | 0.65886  | 0.03738  | 0.58088  | 0.03370  |
| 0.67478  | 0.03899  | 0.64741  | 0.03666  | 0.56862  | 0.03214  |

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