

TRANSPORT AIRCRAFT FLIGHT MODELING FOR THE PURPOSES OF THE AIRCRAFT SYSTEMS EFFECTIVENESS STUDIES

МОДЕЛИРАНЕ НА ПОЛЕТА НА ТРАНСПОРТЕН САМОЛЕТ ЗА ЦЕЛИТЕ НА ИЗСЛЕДВАНЕ НА ГОРИВНАТА ЕФЕКТИВНОСТ НА СИСТЕМИТЕ МУ

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Abstract: An aircraft flight model suited for studying the impact of the aircraft systems on the overall aircraft fuel efficiency is presented. The model is evolved from the Eurocontrol BADA aircraft database. The model is validated by numerical experiment and comparison with flight data obtained from the air transport industry. This work is a part of a project sponsored by the R&DS TU-Sofia.

KEYWORDS: TRANSPORT AIRCRAFT FLIGHT MODELLING, FLIGHT DYNAMICS, AERODYNAMICS OF FLIGHT

1. Introduction

The recent studies of the authors in the field of the aircraft power systems efficiency and effectiveness with respect to the overall aircraft efficiency [5,6] showed the need of more detailed and accurate model of the flight of the aircraft. This model should take account of the particular operational conditions at every stage of the flight and to allow for further modelling of the operating mode of the aircraft power systems. The model was evolved from the Eurocontrol Base of Aircraft Data (BADA) model [1]. The sole BADA is made for aircraft flight path and track studies and could not be used directly for aircraft energy efficiency studies. The verification of the model was made by a comparison of the model results with real flight data, obtained from regular flights. A flight containing the most common types of operation during its stages was chosen. The comparison was made for every single stage of the flight as well for the flight as a whole.

2. Preconditions and means for resolving the problem

In contrast to Eurocontrol BADA operations performance model, in which only the aircraft total energy equations are used [1], in this study multiple approach to describe the aircraft flight is used. The symbol definitions are taken from [3].

For the aircraft ground movement description, with account of the forces acting on the landing gear system of equations (1) was used [3]:

$$(1) \begin{cases} mg \frac{dV}{dt} = P - X - F_x \\ c_y = const \\ X = (c_{x0} + A.c_y^2) \frac{\rho V^2}{2} S \\ N_y = mg - c_y \frac{\rho V^2}{2} S \\ F_x = f.N_y \end{cases}$$

where m is the aircraft mass, g - gravitational acceleration, V - speed, t - time, P - aircraft thrust, X - aerodynamic drag, F_x - tangent reaction in the landing gear, c_y - lift coefficient, ρ - air density, S - wing area, c_{x0} - drag coefficient, A - inductive drag coefficient, N_y - normal reaction in the landing gear, f - friction coefficient.

For the flight trajectory evaluation two different models were used.

1. For horizontal flight and also for climb and descend with known trajectory angle equation (2) in conjunction with system of equations (4) is applied.

$$(2) \quad mg \frac{dV}{dt} = P - X - mg \sin \Theta$$

where Θ is the trajectory angle.

2. For climb and descend with known speed profile $V=V(H)$, equation (3) was deduced from the aircraft total energy equation and replaces the third equation of system (4):

$$(3) \quad \frac{dH}{dt} = \frac{(P - X)V}{mg \left(1 + \frac{V}{g} \frac{dV}{dH} \right)}$$

where H is the flight altitude.

Equation (3) is suitable because it gives directly the connection between the horizontal and the vertical speeds of the aircraft and the distribution of the engine thrust. It can be used in cases of climb with constant calibrated air speed (CAS) or constant Mach number (M), which are common in the transport aviation. The derivate dV/dH is numerically computed for every particular case. This approach differs from the approach of the BADA operations performance model where the expression in the denominator of equation (3) is defined as an energy share factor and is solved analytically or an approximate value for different types of operation is given [1].

Finally system (4) can be transformed in suitable form to get the main flight parameters.

$$(4) \begin{cases} X = (c_{x0} + A.c_y^2) \frac{\rho V^2}{2} S \\ c_y = \frac{mg \cos \Theta}{\cos \gamma} \cdot \frac{2S}{\rho V^2} \\ \frac{dH}{dt} = V \cdot \sin \Theta \\ dm = -C_p \cdot P \\ \frac{d\psi}{dt} = \frac{g}{V} \tan \gamma \end{cases}$$

where ψ is the heading angle, γ - roll angle, C_p - specific fuel consumption. The equations and values of all quantities were taken from BADA and the BADA User manual [1].

The complete model is modularly realised in Matlab. This approach gives freedom to use different parameters to set the boundaries of a single differential equation system for the different phases of the flight. In the model every stage of the flight can be described by one of the four flight cases shown in table 1.

Table 1

| Flight case No | Description | System of equations used |
|----------------|--|--------------------------|
| 1. | Take off run, Landing | (1) |
| 2. | Climb and descend with known trajectory angle, acceleration and turn | (2)+(4) |
| 3. | Horizontal flight | (2)+(4) |
| 4. | Steady climb/descend | (3)+(4) |

3. Flight model verification and discussion

To adjust and verify the model a simulation of a real flight was performed. As a basis flight data from a regular Boeing 737-400 aircraft flight from London to Sofia was used (figure 1). The flight was analysed and divided in separate stages shown in table 2. Using the developed flight model all of the stages were evaluated in Matlab environment.

Table 2

| No | Flight stage | Mode and Configuration Description | Flight case No |
|-----|-----------------|------------------------------------|----------------|
| 1. | Take off run | Gear reactions included | 1 |
| 2. | Initial climb | Acceleration, flaps, gear up | 2 |
| 3. | Climb | Acceleration, flaps, turn | 2 |
| 4. | Climb | Acceleration, flaps up, turn | 2 |
| 5. | Horizontal Turn | | 3 |
| 6. | Climb | Acceleration, flaps up, turn | 2 |
| 7. | Climb | Steady climb | 4 |
| 8. | Climb | Acceleration in climb | 2 |
| 9. | Climb | Acceleration in climb | 2 |
| 10. | Climb | Climb to transition altitude | 4 |
| 11. | Climb | Climb, M=0.78 | 4 |
| 12. | Cruise | Flight level 350, M=0.78 | 3 |
| 13. | Descend | | 4 |
| 14. | Hold | | 3 |
| 15. | Descend | | 4 |
| 16. | Descend | Descend, turn | 4 |
| 17. | Approach | Approach flaps, turn | 4 |
| 18. | Approach | Full flaps, gear up, 3% slope | 2 |
| 19. | Final approach | Full flaps, gear down, 3% slope | 2 |

From table 2 is clear that the flight was complex and included all of the operational procedures performed in normal aircraft operations.

The results show that the model resembles the real flight profile satisfactory, which is displayed on figures 2 and 3. Figure 2 displays the pressure altitude of the flight and figure 3 - the true air speed.

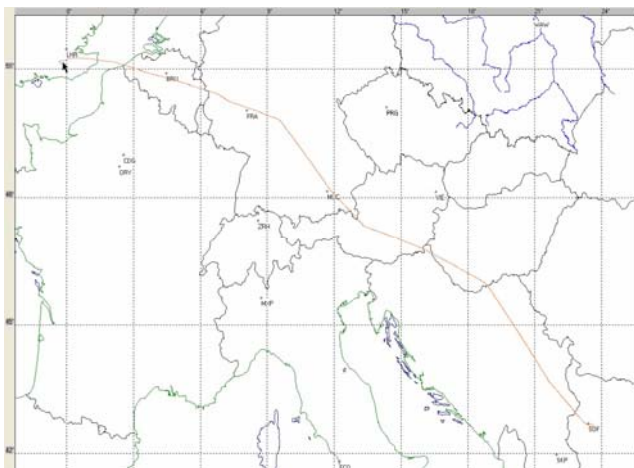


Fig. 1. Flight route

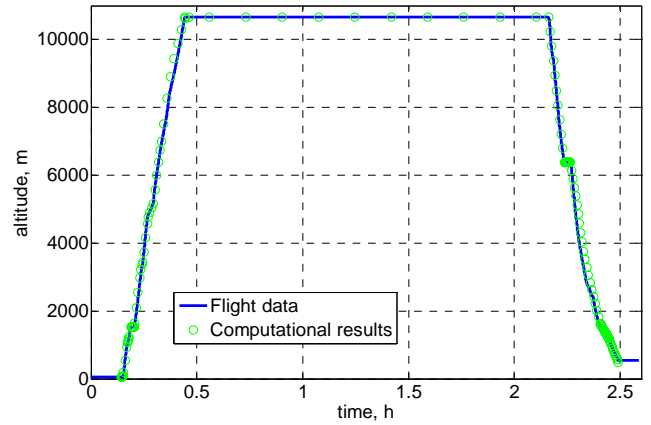


Fig. 2. Flight altitude profile

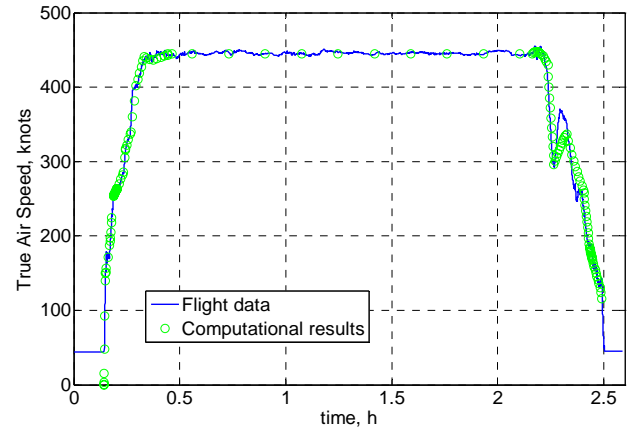


Fig. 3. True air speed profile

A calculation of the maximum deviations of the calculated altitude and the true air speed from those of the flight record was made in table 3.

Table 3

| Flight phase | Parameter | Maximum deviation |
|--------------|---------------------|-------------------|
| Climb | Altitude, m | 260 |
| | True air speed, m/s | 22.6 |
| Cruise | Altitude, m | 4 |
| | True air speed, m/s | 1.6 |
| Descend | Altitude, m | 411 |
| | True air speed, m/s | 16.4 |

These deviations are insignificant in steady flight conditions such as cruise flight. The maximum deviations during the phases of climb and descend can be explained with difficulties in modelling transient modes. The mean deviation is much less and satisfies the accuracy requirements (Table 4).

Table 4

| Flight phase | Parameter | Mean deviation |
|--------------|-------------|----------------|
| Climb | Altitude, m | 39 |
| | % | 1.4 |
| Descend | Altitude, m | 96 |
| | % | 2.6 |

The fuel consumption of the airplane is of special interest as it is directly related with the purpose of this model. The graphical comparison of the model results with the recorded flight data is shown in fig.4. The model results were obtained using the original BADA methodology and airplane data and from fig.4. It is obvious that the computed fuel usage exceeds the values taken from the flight data. The reason can be explained with too high specific fuel consumption computed by the model. An analysis of the BADA data and specific fuel consumption method was performed.

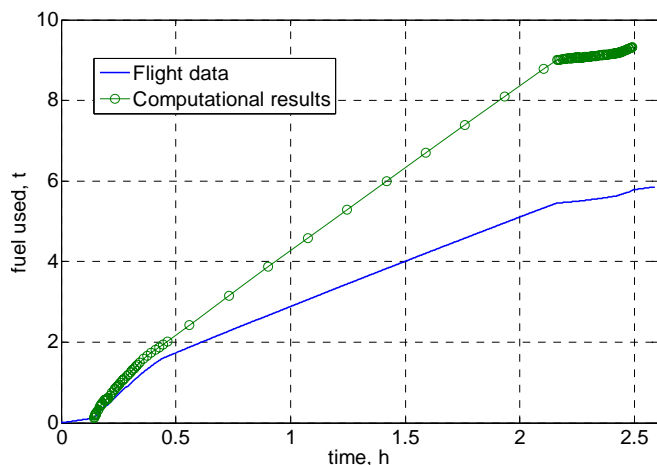


Fig. 4. Mission fuel usage, BADA SFC coefficients

The BADA operations performance model evaluates the specific fuel consumption (C_p) as a function of the true air speed of the airplane in kg/minute/kN:

$$(5) \quad C_p = c_{f1} \left(1 + \frac{V}{c_{f2}}\right) c_{fcr}$$

where c_{f1} , c_{f2} and c_{fcr} are coefficients individual for every type of airplane, c_{fcr} is used only when establishing the specific fuel consumption in cruise flight.

This is an empirical approach for estimating the fuel consumption that has no physical background. Also a mistake in the values of the coefficients was found. The coefficients in BADA version 3.6 for Boeing 737-400 are $c_{f1}=0.9978$, $c_{f2}=9540$ and $c_{fcr}=0.9904$.

The c_{f1} corresponds to the specific fuel consumption of the engines at take off thrust on the ground (zero speed). From the ICAO Aircraft Engine Emissions DataBank, Issue 14 [2], for the CFM 56-3C1 engine used on Boeing 737-400 it was calculated $c_{f1}=0.66$ kg/min/kN.

Empirically for the coefficients c_{f2} and c_{fcr} values of 1600 s/m and 0.75 respectively were chosen. These coefficients must be proven statistically.

The results using these adjusted coefficients are given in figure 5.

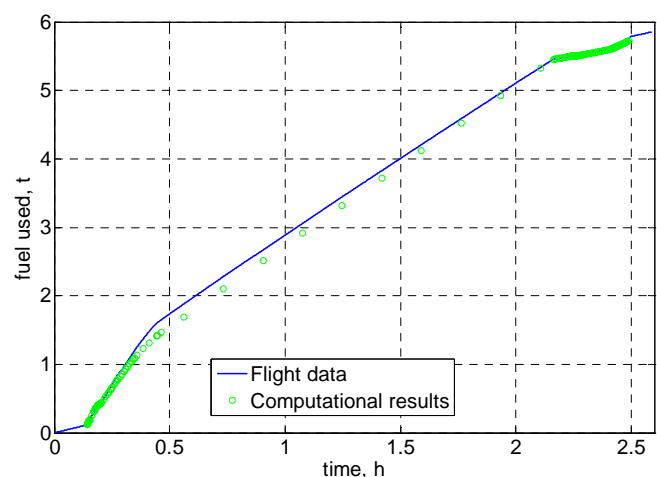


Fig. 5. Mission fuel usage, corrected SFC coefficients

With the new coefficients the maximum error in estimating the aircraft total mass during the flight was reduced to less than 1%.

For idle power or descend conditions in BADA a direct calculation of the fuel flow in kg/min is used. In the recent model this calculation is used only at power less than 10% of the

maximum engine climb power. As visible in the upper left corner of figures 4 and 5 this approach gives good accuracy.

In spite of this the BADA methodology of aircraft fuel consumption evaluation can not be accommodated for the needs of the aircraft systems effectiveness studies.

To assure the accuracy of the model there is a need of application of physically based aircraft engine models for thrust and specific fuel consumption calculation as an approximate function of the altitude and the aircraft speed. These models must not complicate significantly the aircraft mathematical model. It is also possible to use 'Lookup Table' approach, but it is not universal. These are subject to future developments.

4. Conclusions

The following conclusions were made:

- The developed model, based on the Eurocontrol BADA database is applicable for the modelling of all the phases of the transport aircraft flight.
- The mean deviations of the flight parameters are below 3 % when simulating a complex flight.
- The main shortcomings of the model are in the used methods of calculating the aircraft power plant thrust and fuel consumption.
- To overcome this shortcoming a physically based simplified model of the power plant must be developed.

5. References

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