Investigation of fuel savings for an aircraft due to optimization of the center of gravity

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Abstract. The aircraft’s center of gravity (CG) has a significant influence on the safety and efficiency, which are determined to a large degree by keeping the CG position within the forward and aft limits. Improper loading reduces the aerodynamics efficiency of an aircraft, resulting in higher flight drag. This paper focuses on the theoretical analysis of the influence of variable CG parameter on the fuel consumption. A new model is developed to predict the fuel consumption rate for an aircraft with its CG at different position. The numerical result indicates that a more aft CG position produces less drag and, in turn, requires less fuel consumption.

1. Introduction

Today’s and tomorrow’s air transport industry is faced with numerous challenges: safety improvement, fuel saving, emission reduction, noise minimization and cost decrease. Airlines need meticulous management to respond to these challenges. Various optimization strategies, which range from flight management to flight operation and aircraft maintenance, are used to decrease the civil aircraft fuel consumption. [1]

There have been a large number of papers concerned with aircraft fuel savings, especially in the field of trajectory optimization. Various modeling and simulation methods are used to develop and evaluate the fuel burn prediction system for different aircraft types [2-4]. But a very limited amount of research is focusing on optimization of the center of gravity (CG) control for an aircraft.

Weight and balance are two important parameters in the design and operation of an aircraft, and need to be properly controlled to perform the safety and efficiency of the aircraft. For a certain gross weight, the balance depends on the control of the CG.

Aircraft is not allowed to fly overweight, nor is it allowed to fly beyond the CG limits. In addition to the safety factors, the CG also is an important factor in determining the fuel efficiency of the aircraft. If an aircraft is extremely nose down, resulting from too far forward CG position, the tail will need to deflect up more to produce higher downward trim force to maintain the aircraft in level flight. This requires a higher angle of attack (AOA) to generate more lift to balance the aircraft, so additional drag is produced due to the higher AOA, in turn, higher engine thrust is required. [5]

This paper focuses on the theoretical analysis of the influence of variable CG parameter on the fuel consumption. A new model is developed to predict the fuel consumption rate for an aircraft with it’s CG at different position. This model is implemented for Boeing 737-800 aircraft and the numerical result is validated with the Performance Engineers Manual’s data.
2. Theoretical Analysis

2.1. Description of CG
The same as the definition of the CG of other objects, the CG of an aircraft is the point at which the total aircraft’s gravity exerts. The location of CG depends on the distribution of the load on the aircraft. Any weight change of any part on the aircraft can cause the CG to shift, and the CG always moves towards the direction where the weight increases. For a certain gross weight, balance control refers to the control of the CG position.

On large aircraft, the CG is expressed in terms of %MAC, which is a percentage of the length of the mean aerodynamic chord (MAC), as shown in Figure 1. The equation for calculating the position of CG, %MAC, can be written as [5]:

\[
\% \text{MAC} = \frac{X_T}{L_{MAC}} \times 100 \%
\]  

(1)

where \(X_T\) is the distance of CG behind the leading edge of the MAC, and \(L_{MAC}\) is the length of MAC.

Normally, for a modern large aircraft with acceptable flight characteristics, the range of the parameter %MAC is usually between 20% and 30%. Obviously, the greater %MAC is, the more aft position the CG locates.

![Figure 1. Schematic of CG and MAC.](image)

When the CG coincides with the aircraft’s center of lift, the gravity of the aircraft is all balanced by the lift. If this were the case, there is no vertical aerodynamic force on the tail, resulting in zero horizontal trim drag. But this perfectly condition could not happen due to the restriction of stability and safety. The CG of an aircraft must be located within the forward and aft limits for safe flight.

2.2. Flight Aerodynamics
An airplane must be designed to have stability to ensure that it can recover from the interfere of the air flow with hands off the controls. It is important to note that, for fixed wing aircraft the CG is slightly forward of the center of lift, as shown in Figure 2. Because of this architecture, the lift always turns the aircraft nose-down, so nose-up aerodynamic force whose direction is downward has to be produced on the horizontal tail surfaces to balance the aircraft. In a short period of time, the weight of the aircraft is assumed constant. Then the wing's lift is a fixed force independent of airspeed, while the tail's nose-up force varies directly with the airspeed.

For a balanced aircraft in cruise phase (Figure 2), the balance equations, including force balance and moment balance, can be expressed as follows:

\[
L = G + F_{\text{tail}} \quad (2)
\]

\[
L l_1 = G l_2 + F_{\text{tail}} l_3 \quad (3)
\]

where \(L\), \(G\), and \(F_{\text{tail}}\) represent the lift produced by wings, the gravity produced by aircraft gross mass, and the aerodynamic force produced by horizontal tail, respectively; \(l_1\), \(l_2\), and \(l_3\) denote the
corresponding arms of $L$, $G$, and $F_{\text{tail}}$.

![Figure 2. Schematic of aircraft balance.](image)

The lift is produced by wings, with the direction perpendicular to the relative wind, and its magnitude is determined by a number of parameters, including the airfoil shape, air density, air speed and the angle of attack (AOA) of the wing. The lift be expressed as [6,7]:

$$L = \frac{C_L \rho V_{TAS}^2 S}{2}$$

(4)

where $C_L$, $\rho$, $V_{TAS}$ and $S$ are the lift coefficient, the air density, the true airspeed, and the wing reference area, respectively.

The lift coefficient, $C_L$, is mainly determined by the airfoil shape and the AOA. Using Eq. (2) and (4), the lift coefficient is given by:

$$C_L = \frac{2(mg + F_{\text{ail}})}{\rho V_{TAS}^2 S}$$

(5)

The drag coefficient, $C_D$, need to be determined before calculating the drag. Under nominal conditions, $C_D$ is expressed as:

$$C_D = C_{f1} + C_{f2} C_L^2$$

(6)

where $C_{f1}$ is parasitic drag coefficient (dimensionless), and $C_{f2}$ is induced drag coefficient (dimensionless).

Then the drag force can be determined using the drag coefficient, similarly as the lift expression:

$$D = \frac{C_D \rho V_{TAS}^2 S}{2}$$

(7)

2.3. Fuel Consumption

Many factors, such as distance, gross weight, engine performance, cruising speed, altitude, wind, and atmospheric environment, will affect a specific flight fuel consumption. Also, the differences in aircraft configuration and age, as well as the differences in pilots’ operation will affect the level of aircraft fuel consumption. As our focus is the average fuel consumption level of the aircraft, the influence of wind on the fuel consumption level is not considered in this model.

The thrust specific fuel consumption, $\eta$ (kg/(min·kN)), varies depending on the engine type. For gas-turbine engines, $\eta$ is expressed as [7]:

$$\eta = C_{f1} \left(1 + \frac{V_{TAS}}{C_{f2}}\right)$$

(8)

where $C_{f1}$ is the 1st thrust specific fuel consumption coefficient, kg/(min·kN); $C_{f2}$ is the 2nd thrust specific fuel consumption coefficient, knots; $V_{TAS}$ is the true airspeed, knots.

As a product of two values, the thrust specific fuel consumption and thrust, $T_{THR}$, the expression of the nominal fuel flow, $f_{\text{nom}}$ (kg/min), can be written as:
\[ f_{\text{cr}} = \eta T_{HR} \]  

With necessary corrections, the cruise fuel flow, \( f_{cr} \) (kg/min), can be expressed as:

\[ f_{cr} = \eta T_{HR} C_{sf} \]  

where \( C_{sf} \) is the cruise fuel flow correction factor, which varies with aircraft types and flight parameters and provides a more accurate description of the fuel consumption. In this paper the factor is considered as a function of the CG, air speed, gross mass, and altitude.

As thrust equals to drag (\( T_{HR} = D \)) during the normal cruise, replace the \( T_{HR} \) in Eq. (10) with \( D \) in Eq. (7). Consequently, the equation describing cruise fuel flow becomes:

\[ f_{cr} = \frac{\eta C_{sf} C_{s} \rho V_{TAS}^2 S}{2} \]  

3. Results and Discussion

3.1. Numerical Results

A Simulink model was developed based on the equations previously presented for predict the aircraft fuel consumption. This model is implemented for B737-800 aircraft. Our interest is the influence of the CG on the fuel consumption. Figure 3 shows the relationship between drag increase and CG position. The actual variation in drag due to CG depends on airplane design, weight, altitude and Mach. Choosing 22%MAC as the reference CG position, the curves in Figure 3 indicate that, at a given cruise Mach, the drag increases when the value %MAC decreases due to CG position moving forward. In addition, the greater the value \( W/\delta \) is, the more obvious this trend appears. Here, \( W \) represents the gross weight of the aircraft and \( \delta \) is the ratio of flight level ambient pressure to the standard sea level pressure.

![Figure 3. Relationship between drag increase and CG position.](image)

The numerical result is validated with the Performance Engineers Manual’s data. The fuel consumption prediction differences relative to manual’s data are listed in Table 1, presenting the minimal, maximal and average errors. The comparison shows that our model is accurate and reliable, and is a valuable reference for fuel consumption modeling used in aircraft flight manager system. By modifying the corresponding initial parameters, this model can also be used to predict the fuel consumption of other aircraft types, considering the CG position.
3.2. Discussion

The control of weight and balance is one of the core businesses for the airplane operating control center. The CG parameter of an aircraft has a significant influence on the flight safety and the operator’s economic benefits. Improper distribution of the aircraft’s useful load will reduce the flight efficiency, resulting in higher operation cost.

When the CG moves forward, a greater down force on the tail is required to maintain level cruising flight. If the altitude and speed are constant, it requires a higher AOA to produce a higher total wing lift to overcome additional downward force on the tail. At the same time, additional drag is produced due to the higher AOA. In turn, more engine thrust is required, which results in higher fuel consumption.

When the CG moves aft, the required tail trim force is less, so the lift is less, allowing for a smaller AOA. This produces less drag, resulting in less fuel consumption.

In order to achieve the best economic benefits and fulfill the constraint of maneuverability and stability, the operator should proper load and make the CG located near 24% MAC for the B737-800 aircraft.

4. Conclusion

In order to reduce the fuel consumption for air transport industry, investigation of optimized CG position control for an aircraft is conducted. We develop an accurate analytical model for cruise fuel consumption, considering the variable CG position.

Analytical equations are derived and solved. The numerical result indicates that a more aft CG position produces less drag and, in turn, requires less fuel consumption. In addition, the fuel savings due to CG shifting aft have a distinct advantage when the flight altitude and/or gross weight increase. But it is important to note that, for the essential safe flight purpose, CG position must be ahead of aft CG limit.

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