Assessment of the passenger aircraft mass and efficiency with a fuselage without portholes

Abderrafie El Menouni*, Anatolii Kretov and Wang Zhijin
Nanjing University of Aeronautics and Astronautics, Department of Aircraft Design, 211000 Nanjing, China

*E-mail: bidou.aerospace@hotmail.com

Abstract. The problem of evaluating the effectiveness of reducing the weight of the aircraft and, in particular, the use of the concept of "fuel efficiency" is considered. For the design (operational) mass analysis, the mass state equation is used, on the basis of which the method of mass growth coefficients is constructed. The most widely used short-haul and medium-haul passenger aircraft of the B737 and A320 types are considered as an example of the application of this technique. The authors suggest to reduce the weight of the aircraft structure to switch to the fuselage without portholes. In the present work, this decision is assessed from the point of view of saving fuel weight.

1. Introduction
The most important parameter of any aircraft is its mass. When designing the aircraft there is a real struggle to reduce literally every gram. For this, we have to make an elementary assessment - what costs one extra gram of mass, which will be present on the passenger plane.

In this regard, an important issue is the choice of a convenient efficiency parameter that can be used to fairly objectively assess the effect of weight loss. There are various performance parameters that can be used to solve this problem. Since reducing the weight of the structure will eventually affect the reduction of fuel consumption, so we will focus on a parameter related to fuel efficiency.

This parameter can be used to compare the advantage of different aircraft modifications.

To date, fuel efficiency of aircraft $k_{fe}$ is often used as such indicator. The fuel efficiency index is an integral characteristic of the perfection of the aircraft-power plant system. It shows the fuel consumption required to carry one passenger for a distance of one kilometer.

$$k_{fe} = \frac{m_f}{nL}$$

where $m_f$ is the mass of fuel spent for a flight from point "A" to point "B," taking into account fuel consumption on the ground; $n$ – number of carried passengers; $L$ – practical range of flight from point "A" to point "B". This parameter for modern medium-haul aircraft on long-range routes is 19-20 g/(passenger km).

The fuel efficiency at a cost will be determined as

$$c_{fe} = c_{fe} = \frac{c m_f}{nL}$$

Now the average aviation kerosene price is about $c = 0.5$ $$/kg [1].$

In order to solve the task of estimating the cost of new design solutions, it is necessary to determine the cost of transporting a unit of payload mass related to the specific energy spent on the vehicle during its life cycle, its scale, as well as the scale of its production and operation. This will allow to
obtain the main economic characteristics of the whole line of aircraft according to their structural data, as well as the scale of production and operation, which in turn will allow to ensure from the economic point of view the management of the project of development of a new structural solution of the aircraft.

2. Main part

2.1. About fuel efficiency assessments

Three approaches can be used to evaluate fuel efficiency.

The first approach is "global". It requires knowledge of total costs and the number of passengers-miles (kilometers).

CASM (cost per available seat miles) or CASK (or per kilometers) is a commonly and widely used measure of unit cost in the airline industry. CASM is expressed in cents to operate each seat mile offered. In common case it is determined by dividing operating costs by available seat miles. This number is frequently used to allow a cost comparison between different airlines or for the same airline across different time periods. CASM excluding fuel (ex-fuel CASM) is a commonly used measure to compare the cost performance of airlines except the cost of fuel. A natural extension of CASM is revenue per available seat mile (RASM), which helps facilitate a revenue to expense comparison, particularly helpful when comparing rival airlines or results to a benchmark. The share of fuel in this cost is approximately 25% of CASK.

As an example, we will consider the most common medium-line aircraft to date, such as Boeing 737 or Airbas А-320, which belong to the class of narrow-body aircraft (Single-Aisle). According to statistics, the fuel cost of passenger-kilometers for narrow-body aircraft since 2012 is about 4.4 ¢/km [2].

The second way to estimate fuel efficiency can be obtained from the ticket price, which primarily reflects the cost of transportation. It includes direct and indirect costs. Knowing the distance of the flight, and assuming that a quarter of the ticket price (taking into account the average level of profitability of the airline) fall on fuel costs, we can determine the parameter $c_{f.e}$.

And the third approach is the simplest and most accessible, based on the estimation of fuel mass. The total fuel supply can be represented as follows [3]

$$m_f = m_{f.c} + m_{f.beg} + m_{f.end} + m_{f.r} + m_{f.oth},$$

where $m_{f.i}$ are the fuel components: $m_{f.c}$ for the cruising speed; $m_{f.end}$ for descent and landing; $m_{f.r}$ is a navigation reserve; $m_{f.oth}$ - other (for maneuvering around the airfield, testing engines, non-refillable residue). These fuel components in relative masses

$$\bar{m}_{f.i} = m_{f.i} / m, \text{ (m is aircraft mass, can be calculated by the following formulas:)}$$

$$m_{f.c} = (1 - \bar{m}_{f.beg}) * \{1 - \exp[\{V_{cr} - W\}K_{cr} / \{(L - L_{beg & end})gC_{p,cr} \}]]}$$

(4)

(it is taken from the Breguet’s formula on mode $V, K =$ const, $L_{beg & end} \approx 40 H_{cr}, H_{cr} \approx 10-12$ km) [4].

$$m_{f.beg} \approx 0.0035 H_{beg} (1 - 0.03 \psi) / (1 - 0.004 H_{beg})$$  

(5)

$$m_{f.end} \approx 0.002 H_{end} (1 - 0.03 \psi) / (1 - 0.023 H_{end})$$

(6)

$$m_{f.r} \approx 0.9 C_{p,cr} \cdot K_{max}$$

(7)

$$m_{f.oth} \approx 0.006$$

(8)

here $L$ is flight range without spending the navigation reserve, km; $L_{beg & end}$ is the horizontal distance in the climb, acceleration and reduction; $H_{beg}$ is the initial cruising altitude, km; $H_{end}$ is the final height of the cruise flight before the aircraft descends, km; $W$ is the calculated speed of the oncoming wind when flying at altitudes of 10...12 km, $W = 70$ km/h; $K_{max}$ and $K_{cr}$ are the maximum aerodynamic quality and on cruise section, $K_{cr} = (0.89-0.9) K_{max}$; $\psi$ is the degree of double-circuit of the engine; $C_{p,cr}$ is the specific fuel consumption of the engine at cruise mode, kg/N/h.

2.2. Mass growth factor

Considering the equation of mass balance. By functional characteristics it can be represented by the following five parts: target load $m_{ts}$, airframe structure $m_{str}$, power plant $m_{ps}$, fuel system $m_{fs}$, equipment and control system $m_{eq}$.
This scheme of splitting the total mass corresponds to the functional purpose of each component.

*Goal load* is a subsystem whose elements are determined by the purpose of the aircraft: commercial (paid) or combat load; crew, equipment; equipment of passenger and baggage-cargo facilities, weapons.

*The airframe design* is a subsystem, the elements of which are determined by the implementation of the corresponding principle of flight in terms of reliable perception of operating loads. For aircraft, this wing, tail, fuselage and landing gear.

*Power plant* is a subsystem whose elements provide the creation of the required thrust: engines and devices for their installation.

*Fuel system* is a subsystem whose elements ensure the operation of engines during a given flight time on the provided flight modes: fuel and devices for its placement and pumping.

*The equipment and control system* ensure reliable operation of the aircraft its control during the flight.

Representation of the mass of the aircraft in the form of (9) is in accordance with the functional isolation of the five subsystems listed, each of which has its own specifics of mass formation. The goal load is usually specified or determined independently of the total mass. The other subsystems depend on \( m \), and the dependencies \( m_{str} (m) \), \( m_{en} (m) \) are quite close to directly proportional. Dividing equation (9) by the mass of the aircraft yields an equation in the form of relative masses \( \bar{m}_i = m_i / m \).

Let’s assume that one of the functional elements of the aircraft has a change in mass. From equation (9) we get [5]:

\[
\Delta m_{i,0} = m - (m_g + m_{str} + m_{en} + m_{f.s} + m_{eq}).
\]  

Let’s calculate the partial derivative of equation (10) by mass

\[
\frac{\partial \Delta m_{i}}{\partial m} = 1 - \frac{\bar{m}_i \sum \bar{m}_i}{\bar{m}}.
\]  

Moving from partial derivatives to finite increments \( \bar{m}_i \), and given that item \( i \), where there was an initial change in mass \( \Delta m_{i,0} \), you need to take the relative mass not \( m_i \) and \( m_i^* = m_i + \Delta m_{i,0} \), we get

\[
\frac{\partial \Delta m_{i,0}}{\partial m} = 1 - (\bar{m}_{str} + \bar{m}_{en} + \bar{m}_{f.s} + \bar{m}_{eq} + \Delta \bar{m}_{i,0}).
\]  

From the expression (12), we can find the inverse derivative, which is called the mass growth factor (MGF) of the aircraft

\[
\mu_{m,i} = \frac{\partial m}{\partial \Delta m_{i,0}}.
\]  

The MGF shows how many times the total change in the mass of the aircraft will be greater than the primitive (initial) change \( \Delta m_{i,0} \)

\[
\Delta m = \mu_{m,i} \Delta m_{i,0} \quad \text{and} \quad \mu_{m,i} = \frac{1}{[1 - (\bar{m}_{str} + \bar{m}_{en} + \bar{m}_{f.s} + \bar{m}_{eq} + \Delta \bar{m}_{i,0})]}.
\]

Thus, by calculating \( \Delta m_{i,0} \) and \( \mu_{m,i} \) using the expression (13), we can estimate the change in the entire mass.

2.3. Assessment of the mass costs due to portholes

A significant part of the weight of a passenger aircraft is its design. The reduction of its mass is one of the reserves for improving the efficiency of aircraft. As one of the ways to reduce the weight of the aircraft structure, in particular the fuselage, the paper considers the possibility of abandoning the use of portholes and replacing them with monitors, which will not only make it easier for passengers to observe what is happening behind the plane, but will reduce the weight of the structure. Figure 1 shows the draft of aircraft fuselage existing and offered without use of windows. The finite element representation of the panels is represented in figure 2.
Existence of windows and cuts forces to apply the load-carrying frames bordering an opening and distributing loading to them. As a result, the mass of a design significantly increases. In this regard the option in which the fuselage has no cuts under windows is considered, instead of them, monitors are installed, providing passengers with an even more best quality view. At the same time the mass of the fuselage will decrease and there is a problem of economic assessment of application of such design.

Let’s introduce the concept of average surface density of fuselage structure

$$\rho_{\text{fus}} = \frac{m_{\text{fus}}}{A_{\text{fus wet}}}.$$  \hspace{1cm} (15)

To calculate area of washed surface of fuselage we will use formula:

$$A_{\text{fus wet}} = \pi \cdot D_l \left( 1 - \frac{2}{\lambda_f} \right)^{2/3} \left( 1 + \frac{1}{\lambda_f^2} \right).$$  \hspace{1cm} (16)

It is obvious that different areas will have different surface densities, depending on the load and the nature of their structure associated primarily with the existence of irregularities. The entire area is represented as the sum of the parcels of some equal area

$$m_{\text{fus}} = a \sum \rho_i = \rho_{\text{fus}} A_{\text{fus wet}} \text{ from here } A_{\text{fus wet}} = a \sum \rho_i / \rho_{\text{fus}}.$$

Let's select a zone in the area of each porthole with the area

$$a_{\text{pan}} = b_{\text{pan}} h_{\text{pan}}.$$  \hspace{1cm} (17)

To each such rectangle we will apply the most characteristic load that will arise from the internal overpressure and longitudinal force. As a result of the calculation using the Ansys program, we get that the ratio of the mass of the panel with a porthole and without a porthole (Figure 1, b) is subject to their equal strength

$$m_{\text{pan w-}} / m_{\text{pan w-}} = k_{\text{pan}}.$$  \hspace{1cm} (17)

From the condition of ensuring equal strength of these panels, we determine the mass of these panels and the corresponding $k_{\text{pan}}$ coefficient.

These panels form an area with $n_w$ portholes on each board side

$$A_w = 2 \times n_w \times a.$$
Let's assume that the total surface density of a panel with a cutout $\rho_{w+}$ and without a cutout $\rho_{w-}$ is equal to twice the average density

$$\bar{\rho}_{w+} + \bar{\rho}_{w-} = 2\bar{\rho}_{\text{fin}}$$

By solving the equations (17) and (18) we can express the mass of a window section with portholes and without portholes

$$m_{\text{pan w}} = 2/3 k_{\text{pan}} m_{\text{fus}} A_{w},$$

where $m_{\text{pan w}}$ and $m_{\text{pan w}}$ are panel mass with a cutout and without one, subject to their operation at acceptable stresses: $A_{w} = A_{w}/A_{\text{fus wet}}$.

So, the mass difference between the two variants of fuselage will be

$$m_{\text{pan w}} - m_{\text{pan w}} = 2/3 m_{\text{fus}} (k_{\text{pan}} - 1)$$

Next the algorithm of calculation of fuel savings for one flight due to weight reduction will be

$$\Delta m_{\text{fin}} \rightarrow \Delta m = \Delta m_{\text{fin}} = m_{\text{fin}} \Delta m$$

using equation (4).

2.4. Numerical example
Let's consider the case if the fuselage of a passenger aircraft of the A320 type would’ve been made without portholes. We can use an even simpler way to estimate the effect of a cutout on the panel’s mass.

If we take the panel with sizes $a = 0.76$ m $\times$ 0.62 m (Figure 1, b) and $\sigma_{U} = 4893$ MPa, then $m_{\text{pan w}} = 25.227$ kg, and $m_{\text{pan w}} = 18.8$ kg (Figure 2). It means one porthole needs an additional mass of 7 kg. We assume that the mass of glass contained in panels with a cutout, about to be equal to the mass of the monitor instead of window. It means for the whole aircraft with fuselage without 2×40 portholes we will have $\Delta m = 560$ kg.

To calculate the MGF for this type aircraft we take relative masses of functional elements

$$m_{f} = 0.25; m_{st} = 0.3; m_{eq} = 0.1; m_{en} = 0.1; m_{ts} = 0.25.$$

The calculation by using formula (4) gives $\mu_{m, st} = 4$. It means if we redesigned the aircraft while maintaining all its performance characteristics (speed, range, number of passengers), we would eventually get its new mass aircraft $m_{\text{new}} = m - \Delta m_{st} \mu_{m, st} = m(1 - \Delta m_{st} \mu_{m, st})$.

Connection between $m_{f}$ and $\mu_{m, st}$ is $m_{f} = k_{f} m$. For this type aircraft $k_{f} = 1.1$.

Let’s calculate the fuel mass which is need for the aircraft Boeing 737-800 with engines CFM 56-7B26 ($C_{f} = 0.0639$ kg/(N h), $V_{cr} = 830$ km/h, $K_{cr} = 16.6$, $n = 189$) to achieve maximum range 5765 km:

$$m \approx 79 \text{ t}, m_{s} = 18 \text{ t}, m_{\text{beg end}} = 2.4 \text{ t}, m_{t} = 20.4 \text{ t}, k_{f} = m_{f} / (nL) \approx 18.7 \text{ g/pass./km}$$

Then the new aircraft, which is made without windows in the fuselage, will be having

$$m_{\text{new}} = m(1 - \Delta m_{st} \mu_{m, st}) = 79(1 - 0.56/79 \times 4) = 76.8 \text{ t}, m_{t} = 16.5 \text{ t}, m_{t} = 23 \text{ t}, m_{t} = 18.8 \text{ t},$$

$k_{f} \approx 17.2 \text{ g/pass./km}$. New value of fuel efficiency will be

$$C_{\text{f e new}} = C_{\text{f e old}} m_{\text{t new}} / m_{\text{t old}}.$$  

(21)

As a result, reducing the weight of the aircraft will lead to a decrease of $C_{\text{f e}}$.

Knowing the service life of the aircraft (for new aircraft of the type in question, it is about 80,000 flight hours), passenger capacity (with an average load of 60% of the aircraft), average range, aircraft fleet, it is not difficult to calculate what effect will reduce the weight of the fuselage by eliminating the cutouts under the windows. Knowing the number of aircraft operated, you can estimate the overall effect that the proposed version of a lighter fuselage can give. If we take into account the number of aircraft of the considered class was produced (by 2019, Airbus produced more than 9000, and Boeing 327 more than 10,000), it becomes obvious that such design changes can give a tangible economic effect.

3. Conclusion
1. The application of a simple and reliable method for estimating the final mass of the aircraft from the initial changes in the functional elements of the aircraft is shown.
2. A variant of reducing the weight of the fuselage by eliminating the use of portholes and replacing them with monitors that significantly expand the view is proposed. The fuel efficiency of such a proposal was evaluated by reducing the weight of the structure, as a result of reducing the weight of the entire aircraft and ultimately reducing fuel consumption.

3. The developed method for evaluating fuel efficiency can be used in the study of various design options and other functional elements (target load, equipment, fuel system, power plant) and their individual components.

References

[1] IATA Economics. Jet fuel Price monitor. Retrieved from: https://www.iata.org/en/publications/economics/fuel-monitor/

[2] A. Guthorn – Fuel Trends in Aviation. Aero-Engines USA 2013, ICF SH&E. 20/02/2013. Retrieved from: http://www.aeroenginesusa.com/files/2013/03/ICF_SHE_Adam_Guthorn.pdf

[3] Aircraft design / edited By M. A. Poghosyan. - 5th ed., Moscow.: Innovative engineering, 2018. 864 p. (In Russian: Проектирование самолетов/ под ред.М.А.Погосяна. – 5-е изд., перераб. и доп. М.: Инновационное машиностроение, 2018. 864 с.)

[4] Colonel Kip P. Nygren, Major Robert R. Schulz United States Military Academy, 1996, Breguet's Formulas for Aircraft Range & Endurance An Application of Integral Calculus, Session 1265.

[5] Gogolin V. P. Determination of the growth coefficient of take-off weight changes in the implementation of initial changes in the weight of the structure. Works of KAI, Kazan, 1973. vol. 160. P.11-14 (In Russian: Гоголин В.П. Определение коэффициента роста изменений взлетного веса при реализации начальных изменений веса конструкции. Труды КАИ, 1973. Вып. 160. Казань, с.11-14).