AVIATION
ISSN: 1648-7788 / eISSN: 1822-4180
2022 Volume 26 Issue 4: 235–243
https://doi.org/10.3846/aviation.2022.18041

EVALUATION OF WING STRUCTURES AT THE CONCEPTUAL STAGE OF TRANSPORT CATEGORY AIRCRAFT PROJECTS

Anatolii KRETOV [1], Dmytro TINIAKOV [2*]

[1]*College of Aerospace Engineering, Nanjing University of Aeronautics and Astronautics, Nanjing, China*
[2]*College of Civil Aviation, Nanjing University of Aeronautics and Astronautics, Nanjing, China*

Received 27 January 2022; accepted 8 June 2022

Abstract. The purpose of this research is to improve the approach for evaluating of new design solutions based on sensitivity analysis of takeoff mass (SFM) to initial changes in the basic project. The approach is based on the changes assessment in maximum takeoff mass of a developed project or an already existed basic variant of an aircraft with local design (project) changes, including the aerodynamic ones, that ensure the developing of a more advanced aircraft. In comparison with the existed known approaches based on the mass growth factors, which were considered constant, the proposed approach takes into account more exactly the dependence of the takeoff mass on the initial local change in mass in terms of their functional purpose, as well as the aerodynamic characteristics. This approach allows the designer to calculate more precisely the final maximum takeoff mass changes in the early (preliminary) stages of conceptual design when looking for new design solutions. On numerical examples, carried out on the examples of transport category airplanes, a significant dependence of the wing aspect ratio influence on fuel efficiency is shown. The considered approach using SFM with semi-analytical aerodynamic analysis combination is simple, reliable and convenient in the analysis and synthesis of a new project for the design process based on the base variant.

Keywords: evaluation, aircraft, wing, mass sensitivity factor, induced drag.

Introduction

The structural mass is one of the main components of aircraft take-off mass, which in the transport category aircraft is about 30%, of which the wing is about a third. Reduction of the wing mass, as the unit bearing the heaviest load, is therefore one of the urgent tasks that is often presented, and it will continue to face the aircraft designers. The final assessment of the wing's perfection will be based on the economic efficiency of the aircraft. One of the ways for this is to increase the aerodynamic perfection of the wing, as the main lift generator. A rational choice of wing parameters allows increasing the aerodynamic properties of the aircraft, ensuring a decrease in its take-off mass.

It is no coincidence that many researches have been done on these two contradictory problems: mass and aerodynamic perfection of the wing. In particular, much attention has been paid to this problem in such well-known works as Roskam (2004), Haftka et al. (1989), Raymer (2018), Torenbeek (2013), Mieloszyk et al. (2016), Hollmann (1991).

One of the first researches related on the aerodynamic shapes perfection of lift surfaces was the Prandtl study (Prandtl & Tietjens, 2012), where he was the first to theoretically define an optimal wing (a wing with a given lift capacity and minimum induced drag).

On the basis of such a criterion, Carafoli (1956) was the first to determine the theoretically optimal value of the taper ratio of a simple smooth tapered wing, which turned out to be (by his definition) $\eta_{\text{tape.opt}} = 1/2.857$. In references Cummings et al. (2015), Kuchemann (2012), Lyapunov et al. (1999), Raymer (2018), and Riabkov and Tiniakov (2011), the problems of engineering optimization of the wing were solved, based on the optimal distribution of the velocity circulation, taking into account of the induced drag in the free vortex surface and the influence of the suction force on the induced drag. Directions of possible minimization of induced drag is considered by researcher Tiniakov (2012).

Modern finite-element software products with sufficient accuracy allow the analysis of the stress-strain state and provide topological and parametric optimization,

*Corresponding author. E-mail: *tiniakov_d@nuaa.edu.cn*

calculate the aerodynamic performance, and estimate the mass of the aircraft structure. The number of wing variants, in which the contradictions between its mass and aerodynamics can be resolved in the best way, is limited. So, it is better to remove variants with the low efficiency at the early stage. For such a conceptual assessment, when many options are sorted out, it is desirable to have "light" in terms of labor intensity and sufficiently proven approaches. So, at the initial design stages, it may be quite sufficient for thin-walled aircraft structures at first to use a beam model and to use an engineering (theoretical) estimate of wing aerodynamics. Next stage can be the transition to finite element method (FEM) with a small number of one-dimensional rod elements operating in tension-compression and two-dimensional membrane elements. However, it requires the loading level, which in turn depends on the aircraft mass, which is unknown and should be estimated in advance. For aerodynamic analysis: at first, the application of simple analytical models is considered. After that, it is possible go first, for example, to a simple vortex model, and only after that to a more complex Computational Fluid Dynamics (CFD).

The main feature of this research is that it is intended for an initial conceptual assessment of a new aircraft project. It is built on existing (basic) aircraft or projects, on the basis of which an analytical assessment is carried out to improve and refine them for new technical requirements.

The task of aircraft mass reduction is the most urgent task. Various design solutions can provide the increase in some transport category aircraft efficiency indicators, but at the same time it can cause an increasing in its mass. The integrated approach application for solving such a task to avoid the unjustified increase of the aircraft mass. An integrated approach is a combination of several solutions, one part of which makes it possible to increase certain indicators of the aircraft efficiency, and the other part allows for compensation of the aircraft mass increase caused by the first part of the solutions. The development and analysis of such an integrated approach is the task of this research. By changing the aspect ratio, it is expected to reduce the aerodynamic drag of the wing. And, with the use of composite materials, it is supposed to prevent a structure mass increase caused by the aspect ratio increasing.

1. Mass aircraft balance equation

Any new design solutions usually require leading up of the structural mass, which ultimately is reflected in the final (Maximum take-off Mass is MTOM) aircraft mass m_{to}.

The mass evaluation approaches used for aircraft designing are generally classified in four classes. Low class approaches (class I and class II methods) are mostly based on statistical data, while high class approaches specify a prevailing use of analytical calculations. Class I approaches are used at the very early stage of the conceptual design process to evaluate MTOM and its three main parts, namely Operating Empty Mass (OEM), Payload Mass (PLM), Fuel Mass (FM).

This mass can be represented as the sum of the following four functional components:

$$m_{\text{to}} = \sum_{i=1}^{4} m_i = m_{\text{str}} + m_{\text{p.p}} + m_{\text{fuel.s}} + m_{\text{target}}, \tag{1}$$

where, m_{str} is the structural mass (subsystem that includes parts for the aerodynamic principle of flight: wing, fuselage, tail unit, control system, landing gear); $m_{\text{p.p}} = (1 + k_{\text{p.p}})m_{\text{eng}}$ is the power plant mass. This is subsystem that ensures the thrust creation and that includes the engines (mass m_{eng}) and all subunits and subsystems that are necessary for engine operation: nacelles, pylons, thrust reversers, etc. Their proportion is taken into account by the factor $k_{\text{p.p}}$; $m_{\text{fuel.s}} = (1 + k_{\text{fuel.s}})m_{\text{fuel}}$ is the mass of the subsystem that provides feeding to the power plant during the given flight time, including fuel (mass m_{fuel}) and devices for its arrangement and transferring. Their proportion is taken into account by the factor $k_{\text{fuel.s}}$; m_{target} is the target mass. The total mass includes all masses related with the aircraft's purpose. For a passenger aircraft, it is a commercial (payload) mass m_{payload}, as well as the crew mass, mass of equipment for the payload, mass of equipment ensuring reliable and safe flight.

In the general case, the first three components on the right-hand side of Equation (1) are directly dependent on m_{to}, and the fourth component is mainly determined by the aircraft project specification.
Specifics masses application $\bar{m}_i = m_i \times (m_{\text{to}})^{-1}$ provide for us known equation of mass aircraft' balance (in some references it known as aircraft existence equation):

$$m_{\text{to}} = \frac{m_{\text{target}}}{(1 - \bar{m}_{\text{str}} - \bar{m}_{\text{p.p}} - \bar{m}_{\text{fuel.s}})}. \tag{2}$$

Improving the aircraft' structure is one of the ways to ensure the new aircraft success. In each specific design task, the take-off mass can be divided into two components – dependent on m_{to} and independent:

$$m_{\text{to}} = m_{\text{dep}} + m_{\text{indep}}. \tag{3}$$

The target mass is always included in the independent component. If in a new aircraft variant, the designer wants to keep its flight performance, then he should fulfill the next condition: the specific wing load $\bar{p}_{\text{win}} = m_{\text{to}}/S$ and the starting thrust-to-weight ratio $\bar{T} = T_0/(g m_{\text{to}})$ must remain unchanged. With a mass change, a wing area change should be required and the engine requires a new take-off thrust. If the wing area (S = const) and the engine (T_0 = const) are not changed, then these masses can be included in the category of independent components. To keep the same flight range for a new aircraft according to the Breguet's formula, the specific fuel mass $\bar{m}_{\text{fuel}}$ should remain unchanged.

All components of the right-hand side of Equation (2) are weakly dependent on the aircraft mass and are mainly determined by the requirements for this aircraft. They are implemented in the specific aircraft properties at the existing engineering level. In this regard, it is obvious that Equation (2) at the conceptual analysis stage is able to answer the question: what complex of properties can be implemented in a new project, including those which are related with the wing improvement, and which can ensure greater efficiency in the new aircraft.

2. Design method for estimating wing structure mass

Usually, for the initial assessment of the aircraft mass and its main structural members, semi-empirical equations are used. The number of such equations is quite large, but they are applicable only in their structures class and in a rather narrow range of design parameters. For the comparative analysis of the accuracy of mass equations, there are many approaches, most famous of them being presented in the works Raymer (2018), Torenbeek (2013), Roskam (2004), Dababneh and Kipouros (2018). But, in accordance with the topic of this article, the aim is to predict the initial change in the wing's mass, and then evaluate the new aircraft mass based on the existing prototype as a result of any initial changes. In particular, this research was looking at changing of the wing aspect ratio.

In this regard, at the initial design stage, it is useful to apply universal design approaches. For this, the approach proposed in Komarov (2000), Komarov and Weisshaar (2002) was used. The equation for the structural mass estimation is:

$$m = \frac{\varphi C_K l_P P}{\bar{\sigma}_U}, \tag{4}$$

in which all factors affecting the mass are subdivided into five sufficient independent groups: φ is characteristic of the design and manufacture perfection of the structure and its target application ($\varphi > 1$); $\bar{\sigma}_U = \sigma_U / \rho$ is specific strength of material (physical and mechanical properties of the material); C_K is a dimensionless factor that takes into account mainly the load-carrying structure schema and its geometry; P is the reference load; l_P is the reference size.

According to Komarov (2018), for a wing: the reference load $P = n_{calc} g m_{to}$, where n_{calc} is design load factor; the reference size $l_P = S^{1/2}$, where S is wing area. To estimate the C_K factor in general, it is needed to use FEM (Komarov & Gumenyuk, 2002; Komarov et al., 2012). In Kretov and Shataev (2020), on the basis of the analytical approach, research was carried out to estimate the theoretical mass of the fuselage using a beam model for two variants of a structural material: from an aluminum alloy and from a composite material. For conceptual design, as for analyzed case, it is possible to use the already existing weight formulas from Poghosyan (2018), Raymer (2018), Torenbeek (2013), Kowalski et al. (2021) and others. In particular, one of the latest studies in this field can be applied – the LTH (Luftfahrt Technischen Handbuch) – MA401 method (Dorbath & Gaida, 2013). The mass equation for the wing of this study has the form:

$$m_{win} = \frac{2.20013 \times 10^{-4} \times [401.146 \times S^{1.31} + m_{to}^{1.1038}] \times (h/b)_{rep}^{-0.5} A_w^{1.5}}{\cos \chi_{0.25}}, \tag{5}$$

where $(h/b)_{rep}$ is calculated by the airfoil thickness ratio in three characteristic sections: at the root, at the kink, and at the tip:

$$\left(\frac{h}{b}\right)_{rep} = 0.6 \times \left(\frac{h}{b}\right)_{root} + 0.3 \times \left(\frac{h}{b}\right)_{kink} + 0.1 \times \left(\frac{h}{b}\right)_{tip}. \tag{6}$$

As one of the main parameters of the wing design, it was considered the aspect ratio A_w. If the original wing of mass m_{win1} has aspect ratio A_{w1}, then the mass of the new wing with aspect ratio A_{w2} is equal to m_{win2}. If all other parameters are preserved, the ratio of the masses of these wings is according to Equation (4) and Equation (5):

$$\frac{m_{win\,2}}{m_{win\,1}} = \frac{C_{K2}}{C_{K1}} = \left(\frac{A_{w2}}{A_{w1}}\right)^{1.5}. \tag{7}$$

For transport category aircraft with a metal wing and having a regular aspect ratio A_w = 7.5–8.5, it is possible to design a real structure with its higher aspect ratio only in the case of an application of composite materials (CM). Therefore, it is necessary to think about the changes in the wing mass due to the conversion to the CM.

It's time to consider the conversion to the wing from the CM. The permissible stresses can be set taking into account the service life (about 100 000 flight hours), flutter, survivability, lack of buckling, residual strength after corrosion, etc. Also, it is needed to pay attention the additional safety factor values for CM structures η_{CM}. In addition, different manufacturing of the metal and composite wing is leading to different coefficients φ_1 and φ_2. Comparing two wings of the same geometry, but made of different materials, based on Equation (6), can be written:

$$\frac{m_{win\,CM}}{m_{win\,Met}} = \frac{\varphi_2}{\varphi_1} \frac{\bar{\sigma}_1}{\bar{\sigma}_2} \eta_{CM} = k_{CM}. \tag{8}$$

As all these relations in this approximate setting are rather difficult to determine, it was used statistical data. It is shown in Kretov and Shataev (2020) that a properly designed CM structure is approximately 30% lighter than an aluminum alloy structure. Then it is possible to assume that k_{CM} = 0.7.

We can consider the simplest example: a metal wing of rectangular shape. Figure 1 shows the ratio m_{win2} / m_{win1} for a wing with a constant area and variable aspect ratio from A_{w1} = 8 to the aspect ratio A_{w2} = 12, paying attention the same manufacturing process ($\varphi_2 = \varphi_1$). It is leading to a change in the initial structural mass Δm_{str0} according to:

$$\Delta m_{str\,0} = \left(\frac{C_{K2}}{C_{K1}} - 1\right) m_{win\,1} = \left(\left(\frac{A_{w2}}{A_{w1}}\right)^{1.5} - 1\right) m_{win\,1}. \tag{9}$$

Figure 2 shows the dependence of the $m_{win\,2} / m_{win\,1}$ ratio on the sweep angle χ_2 for a wing with a constant aspect ratio and area.

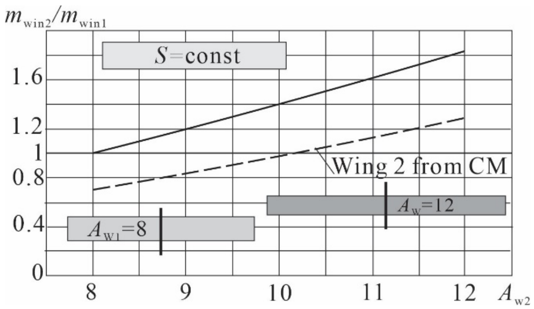


Figure 1. $m_{win\,2} / m_{win\,1}$ ratio depending on wing aspect ratio A_{w2}

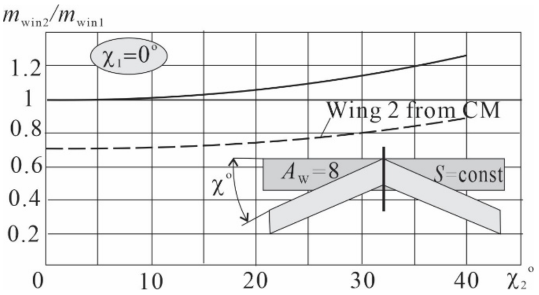


Figure 2. m_{win2} / m_{win1} ratio depending on wing sweep angle χ_2

And finally, to analyze the change in the wing mass made of aluminum alloy due to the transition to CM and to another aspect ratio, taking into account Equation (8) and Equation (9), the following dependence can be used:

$$\Delta m_{str\,0} = \left(k_{CM} \left(\frac{A_{w2}}{A_{w1}} \right)^{1.5} - 1 \right) m_{win\,1} . \quad (10)$$

The dotted lines in Figures 1 and 2 show correspondence to the new design when replacing the metal wing structure with CM.

3. Assessment of the wing geometric parameters influence on the induced drag

It is shown in Carafoli (1956) that the best wing shape is elliptical for the minimal possible induced drag. The modern transport category aircraft wings geometric parameters cannot provide an elliptical distribution of the velocity circulation without additional design solutions (Raymer, 2018; Tiniakov, 2012; Riabkov & Tiniakov, 2011; Chen & Katz, 2004), but one should strive to minimize the induced drag, which can be estimated by the corresponding aerodynamic factor:

$$C_{Di} = \frac{C_L^2}{\pi A_w e_v} \rightarrow \min , \quad (11)$$

where C_L is the lift coefficient, e_v is the span efficiency factor dependent on the distribution of lift along the span which is not necessarily independent of C_L.

The C_{Di} is a determining factor in cruising flight mode. Figure 3 shows the numerical values of various types of drag of the main aircraft units, calculated according to the method of research (Cummings et al., 2015; Riabkov & Tiniakov, 2011) for a medium-range aircraft with a taper wing. At C_L = 0.48, the induced drag coefficient C_{Di} is about 27% of the total aircraft drag.

It is possible to analyze the wing aspect and taper ratios and sweep influence on minimizing the induced drag for a taper wing formed by several trapezoids in the plan view.

To calculate the factor e_v, it was used the equation from Poghosyan (2018):

$$e_v = \frac{1}{1 + 0.02 \dfrac{A_w}{\cos \chi_{0.25}} \left(3.1 - \dfrac{14}{\eta_w} + \dfrac{20}{\eta_w^{\ 2}} - \dfrac{8}{\eta_w^{\ 3}} \right)} , \quad (12)$$

where $\chi_{0.25}$ is swept angle wing by 0.25 of its chords, and η is opposite value to the wing taper ratio.

The result of quantitative assessment of C_{Di} at $C_{L_{cruise}}$ = 0.45, for constant wing area S_w = const according to Equation (11) and paying attention to Equation (12) are given in Table 1.

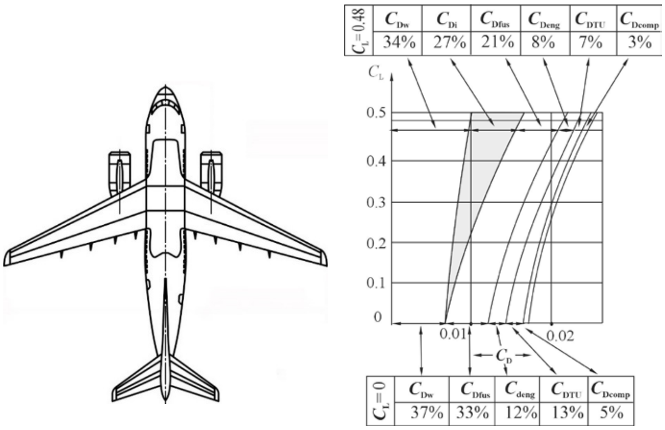
Dependence C_{Di} is shown also in Figure 4, where the constant parameters of taper wing are its taper ratio (η = 1/3.5), its area S_w and lift factor C_L = 0.45. Variable parameters are wing aspect ratio A_w and sweep angle χ.

These data show that changes in the basic wing geometric parameters significantly affect the induced drag.

Based on the calculations performed, it is obviously that by changing the wing geometric parameters, it is possible to effectively influence the induced drag within the presence of given design and manufacture limitations.

Table 1. Dependence of changes in *e* and C_{Di} on sweep and wing aspect ratio

Parameters		e_v					C_{Di}				
A_w		7	8	9	10	11	7	8	9	10	11
χ_{LE}	0°	0.8688	0.8528	0.8374	0.8225	0.8082	0.0106	0.0095	0.0086	0.0078	0.0073
	10°	0.8714	0.8557	0.8405	0.8259	0.8118	0.0106	0.0094	0.0085	0.0078	0.0072
	20°	0.8785	0.8635	0.8490	0.8350	0.8215	0.0105	0.0093	0.0084	0.0077	0.0071
	30°	0.8881	0.8742	0.8606	0.8475	0.8348	0.0104	0.0092	0.0083	0.0076	0.0070
	40°	0.8983	0.8854	0.8729	0.8608	0.8489	0.0103	0.0091	0.0082	0.0075	0.0069



a) b)

Figure 3. Calculated estimate of the airplane drag factor components with a sweep along the leading edge of 28 and a taper ratio of $\eta = 1/3.5$: (a) Aircraft plan view; (b) Graph and values for drag components

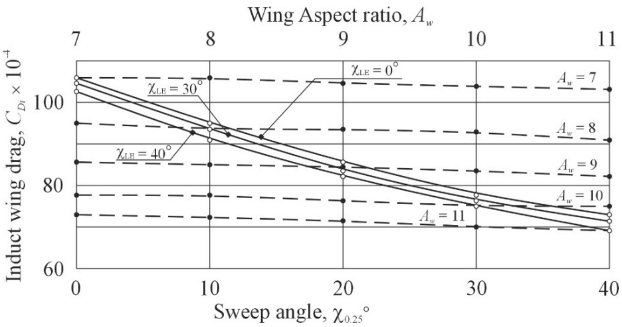


Figure 4. Dependence C_{Di} on sweep and wing aspect ratio with $\eta = 1/3.5$; $C_L = 0.45$; S_w = const

4. Influence of the parameters initial change on the aircraft take-off mass

The assessment of the change from the original (base aircraft) to its new variant can be carried out on the basis of MTOM analysis to the initial change in the n design parameters q_j (Kretov, 2021):

$$dm_{to} = \sum_{j=1}^{n} \frac{\partial m_{to}}{\partial q_j} dq_j . \quad (13)$$

For this study, it was taken into account the initial change in the wing parameter, in particular, its aspect ratio A_w. The aspect ratio change is related to the initial changes: the wing structure mass according to the conditions for ensuring its strength (Δm_{str0}); the aerodynamic performance of the aircraft, in this case, the induced drag; in the mass of the functional components – the fuel and the propulsion system. For small initial changes $\Delta m_{i\,0}$, a linear dependence can be used in the view:

$$\Delta m_{to} = \sum_i \frac{\partial m_{to}}{\partial m_i} \Delta m_{i\,0} = \sum_i \mu_{m\,i} \Delta m_{i\,0}, \quad (14)$$

where $\mu_{m\,i}$ is the sensitivity factor of mass (SFM) of the aircraft, which represents the ratio of MTOM to an initial (local) mass change of the i-th functional mass.

Equations for SFM were obtained in Kretov (2021). In the case of an initial change in the i-th functional mass and preservation of the payload (the fuselage dimensions do not change), they are:

$$\mu_{m\,i} = \frac{1}{\bar{m}_{target} - \Delta\bar{m}_{i\,0} + (\bar{m}_{eng.s} + \bar{m}_{fuel.s})\dfrac{C_{D\,fus}}{C_D}}, \quad (15)$$

where $C_{D\,fus}$ and C_D are the aerodynamic drag factors of the fuselage and full aircraft correspondingly.

The general equation for determining the SFM of an aircraft as a result of changing initial masses of all four possible functional components is as follows:

$$\mu_{m\Sigma} = \frac{1}{\bar{m}_{target} - \Delta\bar{m}_{str\,0} - (\Delta\bar{m}_{eng.s\,0} + \Delta\bar{m}_{fuel.s\,0})\left(1 - \dfrac{C_{D\,fus}}{C_D}\right) + (\bar{m}_{eng.s} + \bar{m}_{fuel.s})\dfrac{C_{D\,fus}}{C_D}}. \quad (16)$$

The final changes of the aircraft mass and its functional components are:

$$\Delta m_{to} = \mu_{m\Sigma} \sum_{i=1}^{4} \Delta m_{i\,0} . \quad (17)$$

Let us calculate the mass sensitivity factors for the aircraft due to the change in the wing aspect ratio $\mu_{m\,str}$ (due to the initial change in the structure mass $\Delta m_{str\,0}$):

$$\mu_{m\,str} = \frac{1}{\bar{m}_{target} - \Delta\bar{m}_{str\,0} + (\bar{m}_{eng.s} + \bar{m}_{fuel.s})\dfrac{C_{D\,fus}}{C_D}} . \quad (18)$$

MTOM change is:

$$\Delta m_{to\,str} = \mu_{m\,str} \Delta m_{srt\,0} . \quad (19)$$

For the aerodynamic drag initial change influence assessment, it was taking into account the obvious proportional relationships $(m_{p.p} + m_{fuel}) \sim T_{cr} \sim C_D$ and $\Delta(m_{p.p\,0} + m_{fuel\,0}) \sim \Delta T_{cr} \sim \Delta C_D = \Delta C_{Di}$, which give the following dependence:

$$\Delta m_{p.p\,0} + \Delta m_{fuel.s\,0} = (m_{p.p} + m_{fuel.s})\frac{\Delta C_{Di}}{C_D} . \quad (20)$$

With accordance to SFM determination by C_D and taking into account Equation (19) and Equation (20):

$$\mu_{m C_D} = \frac{\Delta m_{to}}{\Delta C_{D\,0}} = \mu_m \frac{\Delta m_{p.p\,0} + \Delta m_{fuel.s\,0}}{\Delta C_{D\,0}} = \mu_m \frac{(\bar{m}_{p.p} + \bar{m}_{fuel.s}) m_{to}}{C_D}. \quad (21)$$

The final equation for assessing the change in the aircraft mass due to changes in only the aerodynamic drag (without paying attention the necessary change in the structure mass for the implementation of this effect) is:

$$\Delta m_{\text{to aer}} = \mu_{\text{m}} (\overline{m}_{\text{p.p}} + \overline{m}_{\text{fuel.s}}) m_{\text{to}} \frac{\Delta C_{D0}}{C_{\text{D}}}. \qquad (22)$$

For the μ_{m} determination for Equation (22) it is needed to use Equation (15) with the simple view $\Delta \overline{m}_{i0} = 0$.

The answer about the advisability of a new design solution using (in given case, a wing aspect ratio change) is giving a sign of the total take-off mass change:

$$\Delta m_{\text{to}} = \Delta m_{\text{to str}} + \Delta m_{\text{to aer}}. \qquad (23)$$

A negative Δm_{to} value is providing a corresponding reduction in fuel consumption for the same flight mission.

5. Numerical investigation

To carry out numerical studies on this application approach, it was considered five aircraft of different masses and purposes, the main data for which are given in Table 2.

As the initial data for aircraft, masses are usually given: take-off, payload, empty mass – m_{emp}, fuel, and also the engines. It is the most difficult way to find data on the structure mass within the framework of the considered setting. For this, one can use the empirical mass equations of the above-mentioned LTH method (Dorbath & Gaida, 2013) and separately calculate the masses of the wing, tail unit, fuselage, and landing gear. In the most approximate setting, it is possible to restrict ourselves to statistical data, according to which $\overline{m}_{\text{str}} = 0.25–0.3$ for a given aircraft category. In proposed study, it was taken $\overline{m}_{\text{str}} = 0.275$. The target mass is determined from the following equation:

$$m_{\text{target}} = m_{\text{payload}} + (m_{\text{emp}} - m_{\text{str}} - m_{\text{p.p}}), \qquad (24)$$

where $m_{\text{p.p}} = 1.1\ m_{\text{eng}}$.

By comparing the wings presented in the Table 2, then the main distinguishing feature is that the wing of the MC-21 is made of composite material, which makes it possible to create it with the aspect ratio of $A_{\text{w}} = 11.5$.

New variants of the An-124-100 – 150, C-5A, B737 Max8 and A320 Neo aircraft were considered, whose wings are made of composite material with a new aspect ratio of $A_{\text{w}} = 11.5$, which presents at newest aircraft MC-21 with the best lift-to-drag ratio. For heavy aircraft, it is needed to pay attention for wing span limitations in airport regulations. The final results of this study are presented in the lowest row of Table 2: what fuel economy can be achieved with replacing wings on base aircraft, keeping all other flight performance.

Table 2. Main parameters of five transport category aircrafts

Parameters			Aircraft				
			C-5A, …B (Central Aerohydrodynamic Institute, 1968; Norton, 2003)	An-124-100,… 150 (Antonov, 1993)	B737Max8 (Aviation learning, 2012)	A320Neo (Airbus, 2014)	MC-21-300 (Irkut, 2022; Ilsvik, 2021)
Base aircraft	For cruise flight	V_{cr}, km/h	888	800	852	833	870
		C_{L}*	0.37	0.39	0.51	0.47	0.37
		C_{D}**	0.0415	0.0246	0.0524	0.0264	0.0212
		C_{Di}	0.0126	0.0110	0.0210	0.0179	0.0108
		L/D ratio	17	17.8	15	16.3	18.2
	Wing	Wing span l_{theor}, m	66.8	72.3	35.9	35.8	35.9
		Area S, m^2	575.1	627.3	127	122.44	150
		Taper ratio $1/\eta$	1/3.0	1/4.2	1/3.8	1/4	1/4.37
		Aspect ratio A_{w}	7.8	8.3	9.45	10.45	11.5
		$\chi_{0.25}$,°	25	27	28/25.5	27.4/23.6	29/25.5
		$(h\ /\ b)_{\text{rep}}$	0.12	0.137	0.12	0.137	0.11
	Functional masses	m_{to}, t	348.0	392.0	82.0	73.9	79.25
		m_{payload}, t	120–50	120–80	21.5	20.0	22.6
		m_{emp}, t	147	178	42	42	36
		m_{eng}, t	3.3×4	4.1×4	2.8×2	2.6×2	2.6×2
	Relative masses	$\overline{m}_{\text{fuel}}$	~0.40	~0.50	~0.20	~0.20	~0.20
		$\overline{m}_{\text{p.p}}$	~0.04	~0.04	~0.08	~0.07	~0.07
		$\overline{m}_{\text{str}}$	~0.20	~0.20	~0.28	~0.27	~0.27
		$\overline{m}_{\text{target}}$	~036	~0.26	~0.44	~0.46	~0.46
		$\overline{m}_{\text{to}} = \sum \overline{m}_i$	1.00	1.00	1.00	1.00	1.00
	SFM	$\mu_{\text{m str}}$	2.18	2.48	1.82	1.82	2.17
		μ_{m}	2.03	2.37	1.91	1.85	2.17

Continuation of Table 2. Main parameters of five the transport category aircraft

Parameters				Aircraft				
				C-5A, …B (Central Aerohydrodynamic Institute, 1968; Norton, 2003)	An-124-100,…150 (Antonov, 1993)	B737Max8 (Aviation learning, 2012)	A320Neo (Airbus, 2014)	MC-21-300 (Irkut, 2022; Ilsvik, 2021)
New project	Aspect ratio A_W			11.5	11.5	11.5	11.5	11.5
	Induced drag C_{Di}			0.0088	0.0083	0.0177	0.0165	0.0108
	Drag change $\Delta C_{D\,0}$			–0.0038	–0.0027	–0.0033	–0.0014	0
	Masses change	$\Delta m_{i\,0}$	$\Delta m_{str\,0}$, t	1.14	7.55	–2.15	–0.6	0
			$\Delta m_{aer\,0}$, t	–21.35	–21.84	–1.99	–0.88	0
		Δm_{to}	$\Delta m_{to\,str}$, t	24.9	18.7	–3.9	–1.1	0
			$\Delta m_{to\,aer}$, t	–43.4	–51.7	–3.8	–1.6	0
	$\Delta m_{to} = \Delta m_{to\,str} + \Delta m_{to\,aer}$, t			–18.5	–33.0	–7.7	–2.7	0
	$\Delta m_{fuel} = \bar{m}_{fuel}\ \Delta m_{to}$, t			–7.4	–16.5	–1.5	0.5	0
	$\Delta m_{fuel}/m_{fuel}\ 100$, %			–5.0	–7.8	–9.6	–3.0	0

Notes: * for C_L calculation for the cruise flight mode with the velocity V_{cr} it was applied equation, which corresponds to half of the fuel consumption; ** for the C_D calculation it was taken $\bar{m}_{fuel\ i} = 1.1\,\bar{m}_{fuel\ cr\ i}$, the Breguet formula was applied $\bar{m}_{fuel\ cr\ i} = 1 - \left[\exp\left(\frac{Rgc_p}{(L/D)V_{cr}}\right)\right]^{-1}$, where R is flight range, L/D is lift drag ratio, c_p is the specific fuel consumption.

Analysis of the results of numerical studies with an increase in the aspect ratio of the wings to value $A_w = 11.5$:

1. The change in the mass of the structure has different trends: for C5A (Paterson, 1969) and An-124 it has positive values (increase in mass), for B737Max and A320Neo it has negative values (decrease in mass);
2. The change in the value of the induced drag for all aircraft has a negative value (the induced drag decreases);
3. Since the degree of reduction of the total mass due to the reduction of the induced drag is higher than the degree of increase in the structural mass, the take-off mass of the aircraft with the new wing aspect ratio is less than that of the basic variant of the aircraft;
4. Based on the reduction in take-off mass of the aircraft you can see the decrease of the fuel consumption (3%–9.6%) for all analyzed aircrafts;
5. An increase in the aspect ratio of the wing leads to an increase in the wingspan, which may require the use of special nodes for folding the wingtips.

Conclusions

An original analytical method for evaluating the effectiveness of new design solutions is proposed. This method is based on the proven data from existing aircraft and projects and combines sensitivity analysis of take-off mass, semiempirical structure mass analysis and aerodynamic analytical equations, which makes the proposed method a valid, convenient and effective tool at the initial stages of design.

The influence of changes in the geometric parameters of the wing of an aircraft on its mass in order of decreasing the induced drag and, as a result, increasing the fuel efficiency of the aircraft is investigated. The effectiveness of the use of composite structural materials and the high value of the wing aspect ratio is shown.

Based on the proposed method, an analysis was carried out for some existing aircrafts of the transport category. The conducted study shows the practical efficiency of the proposed approach. The possibility of reducing fuel consumption in the case of the proposed modernization of the base aircraft by switching to a composite wing structure and increasing its aspect ratio is shown (for the AN-124, the reduction in fuel consumption is about 8%, for the Boeing 787 – about 9%).

The proposed method is applicable at the early stages of the design process (preliminary design) and reduces the time and cost of determining more reasonable wing design solutions without additional numerical and laboratory experiments on aerodynamic and strength analysis.

Obviously, in addition to increasing the wingspan, there is a need to use folding wingtips when an aircraft is at the airport. The implementation of this approach for the new Boeing 777X clearly demonstrates the proof of this concept. As the next stage of this study, the authors plan to include the influence of wing tip folding nodes in the design evaluation.

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Notations

A_w – wing aspect ratio;
C_D – aerodynamic drag coefficient;
$C_{D\ TU}$ – tail unit drag coefficient;
C_{Dcomp} – compressibility drag coefficient;
C_{Deng} – engine and engine nacelle drag coefficient;
C_{Dfus} – fuselage drag coefficient;
C_{Di} – induced drag coefficient;
C_{Dw} – wing drag coefficient;
C_K – dimensionless factor characterizing the structure load-carrying scheme, and the nature of its loading;
C_L – lift force coefficient;
$C_{Lcruise}$ – lift force coefficient for cruise flight mode;
e_v – span efficiency factor;
h/b – airfoil thickness ratio;
$k_{fuel.s}$ – $m_{fuel.s}/m_{fuel}$ – 1;
$k_{p.p}$ – $m_{p.p}/m_{eng}$ – 1;
l_p – reference size;
m_{dep} – mass dependent on m_{to};
m_{eng} – engine mass;
m_{fuel} – fuel mass;
$m_{fuel.s}$ – fuel system mass;
m_{ind} – mass independent on m_{to};
$m_{p.p}$ – power plant mass;
$m_{payload}$ – payload mass;
m_{str} – structural mass;
m_{target} – target mass;

m_{to} – maximum take-off mass;
m_{win} – wing mass;
$\bar{m}_i = m_i / m_{to}$ – mass fraction;
P – reference load;
p – specific wing load;
S_w or S – area of the wing;
φ – the coefficient taking into account the nonstructural elements and deviation from the theoretical variant in favor of manufacturability;
η_w or η – taper ratio or opposite value to taper ratio (West country);
$\chi_{0.25}$ – swept angle wing at 0.25 chord;
χ_{LE} – swept angle wing at leading edge;
μ_m – mass sensitivity factor;
ρ – structural material density;
σ_U – permissible stress.