Comparison of Economic and Transport Capabilities of Heavy C-type Airfield-Based WIG [Wing-in-Ground-Effect] Craft Versus Passenger Aircraft

A N Luchkov¹

¹Moscow Aviation Institute (National Research University), Moscow, Russia
E-mail: a.luchok.n@gmail.com

Received xxxxxx
Accepted for publication xxxxxx
Published xxxxxx

Abstract

This article assesses the potential increase in the transport and economic characteristics of heavy cargo and passenger aircraft, if they are processed into WIG craft. This type of air transport is of interest from the point of view of improvement of characteristics from the position of mass use on the airways that pass mainly over the water surface of seas and oceans, as 75% of international air transport is accounted for by these airways. Classic amphibious WIG crafts are known to have extremely low performance due to their high aerodynamic resistance, high structural weight and increased fuel consumption in take-off/landing modes. The solution to this problem may be to switch to airfield take-off WIG crafts. As part of the work, boundary conditions for the study were developed, and a set of formulas was developed to allow for a recalculation of fuel and payload redistribution depending on the operating conditions. The results include changes in gross weight, transport and fuel efficiency, as well as potential changes in aircraft operating costs.

Keywords: WIG Craft, efficiency, airfield takeoff, aerodynamic quality, fuel consumption

1. Introduction

Currently, there is a problem of increasing the speed of cargo delivery to remote areas, separated by large water areas. One of the solutions to this problem may be the use of WIG [wing-in-ground-effect] craft, which, as shown in [1], can provide much higher speeds of movement than river and sea vessels, with higher aerodynamic and seaworthiness (including amphibiousness) compared to hydroplanes.

The work on the study of various layouts and schemes of heavy transport screens was carried out, for example, in the corporation Boeing. As part of the Pelican Ultra program, a super WIG craft project with a maximum takeoff weight of 2700 and 5000 tons, a payload of 1280 and 2500 tons, respectively, and a cruising speed of 490 km/h was piloted and developed. In the course of analysis of transport scheme variants, the drawbacks of marine WIG craft of the aircraft scheme were revealed. Thus, due to the peculiarities of take-off/landing operations from the water there are increased requirements to their strength. Typical requirements for them are wing design with low values of relative elongation, horizontal stabilizer of large area and range, excessively powerful engines to ensure effective takeoff from the water surface. All these negative factors significantly reduce the practical value of the marine WIG craft and make it ineffective in flight. As a result of the research, Boeing specialists decided...
to design the Lands without presenting water-based conditions. This resulted in a decrease in the weight of the empty WIG craft by 20–25% due to a decrease in the requirements for the frame strength, which led to a decrease in the weight of the vehicle and the required power plant capacity.

Economically, the effect of the screen reduces the fuel consumption of a cruise WIG plane, which is not directly related to its basing system, which is important for the operation of a high-speed ship. Currently, there are two concepts of using WIG-plans in transportation systems. The first concept — "airport — water area — airport" — provides for takeoff of the WIG-plane from the airfield, flight at an altitude of 6–11 km or over the water area in the near-screen mode and landing at the airport of destination. The second concept — "seaport — water area — seaport" — provides for the basing of the WIG-plane on the coastline, including landing on water, if necessary, and landing in the port of destination [2].

The experience of operation of Russian heavy WIG-planes of the concept "seaport — water area — seaport" with blowing and its subsequent detailed analysis performed in several countries of the world [3–9] has revealed a few their significant drawbacks:

- low aerodynamic quality (within 13–16 units);
- low relative useful mass (useful return);
- significant energy-to-weight ratio (directly for the WIG craft plan, due to the lift and mainframe engines);
- high power consumption on take-off/landing modes;
- insufficient seaworthiness (mainly of light screen-planes);
- low comfort and environmental friendliness.

In order to improve the operational and economic performance of heavy WIG-planes and reduce the financial costs of maintaining the overall life cycle, it is proposed to avoid takeoff/landing from the water surface, which in turn will lead to:

1. Refusal to use the lifting-march propulsion system, which will be replaced (to compensate for the thrust-to-weight ratio at altitude) by two-circuit propulsion systems with a high degree of dual-circuit efficiency, and consequently, to reduce fuel consumption;
2. Reducing the hull strength requirements of the vessel and, therefore, reducing the weight of the glider structure;
3. Redistribution of useful fuselage volumes;
4. Possibilities to install a large elongation wing with equivalent bearing surface area to increase the aerodynamic quality of K.

2. Assessment of changes in the transport efficiency of passenger and cargo aircraft

The perfection of a transport vessel as a complex technical system is characterized by various types of efficiency (weight, economic, transport, operational, etc.), for which several efficiency criteria have been developed. Each of them has its own rational field of application, objectively characterizing those or other aspects of creation and functioning of a ship and allowing to solve a certain range of tasks of this or that stage of a life cycle of an aircraft (its conceptual or general designing, manufacturing, operation, etc.).

We will accept as criteria of mass and transport perfection of cargo and passenger WIG-plane the relation of mass of the empty equipped WIG-plane to ton-kilometer of transported cargo:

\[ A = \frac{m_{oe}}{m_p \cdot L} \]  

(1)

where: \( m_{oe} \) — operational empty weight, t; \( m_p \) — payload, t; \( L \) — flying range, km.

With this methodical approach, the mass of an empty WIG-plane is no less important than the weighted return on the WIG-plane's transport efficiency. At the given values of payload and flight range the most economical WIG craft plane diaphragm with a minimum value of \( m_{oe} \). The size and, consequently, tonnage of the WIG-plane determine its load-carrying capacity and flight range, therefore, it is expedient to refer the mass of the empty loaded plane to the product of the flight range and payload \( m_p \cdot L \).

The first part of the study assumes calculation of transport efficiency for passenger and cargo category aircraft, the second part — for WIG-planes.

3. Boundary conditions

The following assumptions and restrictions were made in order to study changes in the transport efficiency of heavy passenger and cargo aircraft:

The study was carried out for two aircraft loading cases:

a. Maximum take-off weight (maximum fuel volume + fuel reserve, \( L_p = \text{const} \));

b. Maximum take-off weight (maximum fuel volume + payload, \( L_p = \text{const} \));

In the calculations of transport efficiency, it was assumed that the WIG crafts have been designed by deep processing of the aircrafts studied;

The maximum take-off weight, the relative weight of the empty equipped basic version of the aircraft and the screen-plane created on its basis are equal;

Maximum fuel volumes of the basic versions of aircraft and WIG-planes are equal;

Fuel costs for take-off of basic versions and WIG-planes are equal;

Cruising speeds, aerodynamic quality, and consumable characteristics of passenger and cargo aircraft were taken from open sources [10–13].

Cruising speed for WIG versions of aircraft was assumed to be 450 km/h;
Average flight aerodynamic quality of K was assumed to be 40 (flight support at short and ultra-short distances from the screen);

Specific fuel consumption of Ce (H=0; M=0) and throttle characteristic of φ for airplanes and WIG-planes are assumed to be equal;

High-speed characteristics of power units were taken from open sources;

In order to get the maximum values of transport efficiency of the WIG -plans it was assumed that the whole flight at a given distance passes near the screen;

The study of transport efficiency of passenger, cargo planes and WIG-planes was carried out from the condition that \( L_p = \text{const} \) in each calculated case;

It is assumed that during the flight on the screen, considering the accepted weight, aerodynamic and flight characteristics of the aircraft, will have the best indicators of kilometer and hourly fuel consumption. Therefore, based on condition 12, the released mass of fuel should be compensated for by the payload to meet condition 1.

The transport efficiency was calculated for the following aircraft groups:

a. Passenger planes: A310-200, A310-300, A318-100, A319-100, A320-200, A321-100, A321-200, A319neo, A320neo, A321neo, A330-200, A330-300, A340-200, A340-300, A340-500, A340-600, A350-800, A350-900, A350-1000, A380, MD-83-88, MD-90, B737-700, B737-800, B737-900, B747-100, B747SP, B747-200, B747-300, B747-400, B747-81, B757-200, B757-300, B767-200, B767-300, B767-300, B767-300, B777-200ER, B777-700, B777-200ER, B777-200LR, B777-300, B777-300ER, B777-9, Tu-204-120, Tu-214, Tu-204-300, Il-96-300, Il-96-400M, MC-21-300. The graphs below show the division into medium and long-haul by maximum takeoff weight; all aircraft belong to the same category in ICAO standards.

b. Cargo aircraft: Tu-204, B727, B737-700, B757-200, DC-10, A300, Tristar, Il-96-400T, B747-400F, B747-8F, B767-200, A380-800F, An-124, Il-76T, An-12, L-100, L-500, An-225.

4. Analysis of changes in the transport efficiency of passenger and cargo aircraft

Calculation case 1. Calculation of transport efficiency was performed by formula (1). To calculate the transport efficiency of cargo and passenger screens, the formula (2) modified using formulas from sources [10, 14] was used, considering changes in flight, aerodynamic and consumable characteristics of aircraft.

\[
A = \frac{m_2}{(m_p - m_f - m_{oe}) \left( 1 - \frac{m_f}{m_0} \right)^2} 
\]

where: \( m_0 \) — maximum takeoff weight, t; \( m_f \) — weight of fuel, t; \( m_p \) — payload in the WIG-plan mode, t; \( L_p \) — practical range, km; \( m_p \) — payload, t; \( C_e_{WIG} \) — WIG specific fuel consumption; \( K_{WIG} \) — WIG aerodynamic quality; \( V_{WIG} \) — WIG cruising speed.

Calculation case 2. The payload for Calculation Case 2 can be determined as the difference between the maximum takeoff weight \( m_0 \) and the weight of the loaded and fully loaded aircraft. The following formula was used to calculate the transport efficiency of aircraft:

\[
A = \frac{m_2}{(m_0 - m_f - m_{oe}) \left( \frac{C_e_a V_{a}}{m_0} \left( \frac{1}{1 - m_f/m_0} \right) \right)} 
\]

where: \( m_p \) — payload in the WIG-plan mode, t; \( m_f \) — fuel fraction, t; \( m_p \) — payload, t; \( C_e_a \) — aircraft specific fuel consumption; \( K_a \) — aircraft aerodynamic quality; \( V_a \) — aircraft cruising speed.

It is proposed to use formula (4) for WIG-planes, which is a modification of formula (3) by recalculation of payload mass due to reduction of fuel mass during movement in WIG-plan mode.

\[
A = \frac{m_2}{(m_p - m_f - m_{oe}) \left( \frac{C_e_{WIG} V_{WIG}}{m_0} \left( \frac{1}{1 - m_f/m_0} \right) \right)} 
\]

For Case 2, the average increase in transport efficiency is 2-fold. In both cases, the increase in transport efficiency is due to an increase in mass output.

5. Analysis of changes in economic efficiency of passenger and cargo aircraft

Economic efficiency (EE) is an indicator that demonstrates the cost of aircraft operation, income and net profit. When calculating, the dimension of EE, as a rule, is taken as an equivalent for passenger planes [rub (USD)/1 pass.], for cargo — [USD(USD)/1 kg of cargo]. EE is one of the most important indicators of aircraft competitiveness along with transport efficiency. One of the indicators of EE is the cost price, which consists of many difficult to calculate parameters. One of the most significant cost parameters is the cost of fuel and lubricants, which according to ICAO documentation is about 33% [9]. Within the framework of this work, an assessment of the change in fuel efficiency when comparing aircraft and WIG-planned vehicles was made.

Fuel efficiency. Fuel efficiency, i.e. fuel consumption per unit of transport work, is one of the most important parameters for evaluating the efficiency of transport category aircraft. The level of fuel efficiency mainly depends on specific engine fuel consumption, aerodynamic and weight perfection of the aircraft, its passenger capacity (carrying capacity).
For cargo aircraft:
\[ q = \frac{m_t}{m_{\text{lp}}} \left( g \frac{m_p}{k \text{g} \text{km}} \right), \quad (6) \]
where: \( m_t \) — weight of fuel, g; \( N_{\text{pass}} \) — number of passengers; \( L_p \) — practical range, km; \( m_p \) — payload.

We obtain the mass of fuel for passenger and cargo screenplanes by recalculating according to the Breguet formula [15] with the condition of changing the basic flight-technical, aerodynamic and consumable characteristics in accordance with the conditions. We will accept the following formula to calculate the fuel efficiency of passenger screens:
\[ q = m_0 (1 - \frac{1}{\text{EXP}(\frac{L_{eWIG} K_{WIG} V_{WIG}}{C_{eWIG}})}) \left( N_{\text{pass}} + \frac{[m_t - m_{p}'] m_0}{m_{\text{opkl}}} \right) \left( \frac{1}{1 - m_f} \right), \quad (7) \]

For cargo WIG-planes:
\[ q = m_0 (1 - \frac{1}{\text{EXP}(\frac{L_{eWIG} K_{WIG} V_{WIG}}{C_{eWIG}})}) \left( m_p + (m_t - m_{p}') m_0 \right) \left( \frac{1}{1 - m_f} \right), \quad (8) \]

where: \( m_0 \) — maximum takeoff weight, kg; \( m_{p} \) — WIG fuel fraction; \( m_{\text{opkl}} \) — weight of one passenger with luggage, kg; \( L_{eWIG} \) — number of passengers; \( L_p \) — practical range, km; \( m_p \) — payload in the WIG-plan mode; \( C_{eWIG} \) — WIG specific fuel consumption; \( K_{WIG} \) — WIG aerodynamic quality; \( V_{WIG} \) — WIG cruising speed.

Calculation case 2. Calculation Case 2 involves a recalculation of the fuel efficiency for a fully fueled aircraft with a maximum take-off weight.

The fuel efficiency of passenger aircraft can be calculated using the following formula:
\[ q = \frac{m_t}{m_{\text{opkl}}} \left( \frac{K_a V_a}{C_{eA}} \frac{1}{\text{EXP}(\frac{L_{eWIG} K_{WIG} V_{WIG}}{C_{eWIG}})} \right) \left( \frac{1}{1 - m_f} \right) \left( \frac{1}{m_f} \right), \quad (9) \]

Cargo aircrafts:
\[ q = \frac{m_t}{m_{\text{opkl}}} \left( \frac{K_a V_a}{C_{eA}} \frac{1}{\text{EXP}(\frac{L_{eWIG} K_{WIG} V_{WIG}}{C_{eWIG}})} \right) \left( \frac{1}{1 - m_f} \right) \left( \frac{1}{m_f} \right), \quad (10) \]

where: \( m_f \) — fuel fraction; \( m_p \) — payload in the WIG-plan mode, t; \( C_{eA} \) — aircraft specific fuel consumption; \( K_a \) — aerodynamic quality; \( V_a \) — cruising speed.

The fuel efficiency of passenger WIG-planes can be determined by the formula:
\[ q = \frac{m_0 (1 - \frac{1}{\text{EXP}(\frac{L_{eWIG} K_{WIG} V_{WIG}}{C_{eWIG}})})}{(N_{\text{pass}} + \frac{[m_t - m_{p}'] m_0}{m_{\text{opkl}}} \frac{1}{C_{eA}} \frac{K_a V_a}{C_{eA}} \text{EXP}(\frac{L_{eWIG} K_{WIG} V_{WIG}}{C_{eWIG}}) \left( \frac{1}{1 - m_f} \right))}, \quad (11) \]

Cargo WIG-planes:
\[ q = \frac{m_p (1 - \frac{1}{\text{EXP}(\frac{L_{eWIG} K_{WIG} V_{WIG}}{C_{eWIG}})})}{m_p + (m_t - m_{p}') m_0 \frac{1}{C_{eA}} \frac{K_a V_a}{C_{eA}} \text{EXP}(\frac{L_{eWIG} K_{WIG} V_{WIG}}{C_{eWIG}}) \left( \frac{1}{1 - m_f} \right))}, \quad (12) \]

6. Conclusions

Based on the studied literature, it was possible to get acquainted with a complex of advantages and the lacks designed WIG-planes. The main drawbacks of the existing WIG-planes are the relatively high weight of the construction, power system, increased fuel consumption especially in takeoff modes and low aerodynamic quality (13–16 units), which in turn has a negative impact on the efficiency and effectiveness. The easiest way to solve these problems is to switch from the concept of an amphibious WIG-plane to WIG-plane, which can be based only on prepared airfields.

Heavy passenger WIG-planes type C of the “Airport — water area — airport” concept are a prospective type of air transport from the point of view of increasing transport efficiency by increasing the weight of commercial return (up to 70–75% on average), by reducing fuel consumption while moving in the area of the screen effect. At the same time, the best indicators of weight efficiency are those aircrafts, 100% of the way of which passes over the water surface. The general trend of change in the total weight return can be estimated from Fig. 1 a, b.

Fuel efficiency of type C WIG-planes can be increased in average by 1.8–2 times due to the increase of aerodynamic quality and reduction of specific fuel consumption of the power unit, which, in general, reduces the cost of operation of such aircraft by 15–17% on average as compared to conventional aircraft (Fig. 2 a, b).
Figure 2. Change in kilometer-long fuel consumption of passenger and cargo aircraft.

References

[1] Yun L, Bliault A and Doo J 2010 *WIG Craft and Ekranoplan* (New York: Springer)

[2] Panchenkov A N, Drachev P T and Lyubimov V I 2006 *Expertise of the screen-planes* (Novgorod: VGAVT)

[3] Jia Q, Yang W and Yang Z 2016 *Numerical study on aerodynamics of banked wing in ground effect* (Shanghai, China: Tongji University)

[4] Jamei S*, Maimun A and Azwadi N° 2018 *Ground boundary layers effect on aerodynamic coefficients of a compound wing with respect to design parameters* (Iran: Department of Marine Engineering, Faculty of Engineering, Persian Gulf University, Boushehr)

[5] Park H 2017 *MATEC Web of Conferences* 139 00022

[6] Kinaci O K, Cosgun T, Yurtseven A and Vardar N 2017 *Ground effect or grounding: Which happens when?* (Istanbul, Turkey: Yildiz Technical University)

[7] Mascalik A I, Nagapetyan R A and Lukyanov A I 2013 *WIG-planes transport ships of the future* (St. Petersburg: Shipbuilding)

[8] Nebylov A and Nebylov V 2014 Wing-in-ground effect vehicles flight automatic control systems development problems. *5th AEROTECH conference Kuala Lumpur, Malaysia* 629 pp 370–5

[9] Gadalov V V, Gapoov M A and Kuteynikov M A 2007 Wing-in-ground (WIG) craft (ekranoplan). Practical aspects of the classification and survey according to RS instruments 9th International Conference on Fast Sea Transportation Shanghai, China pp 76–9

[10] Fortinov L G, Kobyzev G, Zabaluyev I and Sokolyansky V 2002 Assessment of the average aerodynamic quality of mainline jets on cruising modes of flight *Proceedings of the conference Getelndzhek-2002* (Moscow: TsAGI printing house) pp 200–4

[11] Arutyunov A G, Dydyshko D V and Kuznetsov K V 2016 History of transport aircraft development *Proceedings of MAI 89* http://trudymai.ru/published.php?ID=72654

[12] Arutyunov A G, Dydyshko D V, Yendogur A I, Kuznetsov K V and Tolmachev V I 2016 Prospects for the development of transport aircraft *Proceedings of MAI 90* http://mai.ru//upload/iblock/d01/arutyunov_dvydshko_endogur_kuznetsov_tolmachev_rus2_1.pdf

[13] Shaynin V M 1962 *Weight and transport efficiency of passenger planes* (Moscow: Oboronghiz)

[14] Torenbeek E 1976 *Synthesis of subsonic airplane design* (Rotterdam: Nijgh-Wolters-Noordhoff Universitaire Uitgevers B V)