

AN “INTEGRATION INDEX” FOR DETERMINING THE DEGREE OF SUBSYSTEM INTEGRATION IN PASSENGER AND TRANSPORT AIRCRAFT DESIGNS

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ABSTRACT

This study addresses the scientific and technical challenge of evaluating the integrative properties of the complex technical system comprising an aircraft's airframe and power plant during the phase of work on the preliminary design or modernization of passenger and transport aircraft. A novel “integration index” is proposed, which quantifies the degree of subsystem integration or compatibility by considering thrust, aerodynamic, and geometric characteristics, alongside design and layout solutions. The integration index may streamline early-stage parametric studies, by reducing design variants. The integration index's dependencies on the characteristics of the aircraft engine and airframe are examined. The proposed approach can be used to conduct parametric studies at the stages of preliminary variant design of aircraft subsystems. This, in turn, will reduce the cost and time of designing new, significant upgrades of existing aircraft and their components. The methodology offers a practical tool for evaluating hybrid-electric and conventional aircraft systems, thus guiding the development of innovative and competitive aviation technologies.

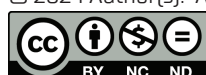
Keywords

complex method, parametric appearance, propulsion system, airframe, degree of rationality, integration, technical perfection.

1. INTRODUCTION

Given today's rapid technological advancements and generational shifts in aviation equipment, the ratio between the time required for the development of an aircraft or its power plant (PP) and the duration of its operation is significantly shifting. As is well known, the design development stage often extends over prolonged periods, making it necessary to intensively strive to reduce the time spent at all stages. This, in turn, requires a search for comparatively time-efficient methods of identifying consistent indicators for aviation equipment at the early (pre-sketch)

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stages of development. The theoretical basis for such methods lies in comparing and evaluating design options at the conceptual level.

The technical sophistication of an aircraft's PP is crucial for achieving qualitatively new flight and technical performance characteristics. This means it is essential to study the PP as an integral part of the aircraft design. The choice of a particular aviation control system is determined by the requirements that are imposed on the aircraft. At the same time, the PP acts as the object of evaluation, with the aircraft as a means of evaluating the technical solutions made. This task is typically resolved by conducting flight tests, but given that a modern aircraft is a complex technical system, full-scale tests often fall short of achieving the specified performance indicators due to the integrative properties of the aircraft. As emerging integrative properties may be undesirable (or even unacceptable) for the technical system, it is desirable to foresee them at the stage of comparing options, in order to ensure the consistency of the indicators and characteristics that make up the aircraft as a complex technical system.

The challenge of synthesizing subsystems is further complicated by the fact that both the airframe and the PP themselves, in turn, are complex technical systems [1, 2]. All this together can result in a failure to achieve the specified design indicators of a transport or passenger aircraft, rendering such aircraft uncompetitive in the aviation market. Therefore, the scientific and technical task of developing a comprehensive indicator of the degree of integration between the characteristics of the PP and the airframe of a transport or passenger aircraft becomes critical.

Nomenclature

A/C	– Aircraft;
DOH	– Degree of Hybridization;
EG	– Electric generator;
EM	– Electrical Motor;
EPP	– Electric Power Plant;
FC	– Fuel Cell;
GTE	– Gas Turbine Engine;
H _E	– Hybridization for Energy;
H _P	– Hybridization for Power;
HPP	– Hybrid Power plant;
M	– Mach number;
MTOM	– Maximum Take-Off Mass;
MTOW	– Maximum Take Off Weight;
PAX	– Passengers;
PFEE	– Payload-fuel energy efficiency;
PP	– Power plant;
PS	– Propulsion system;
SP	– Specific power.

1.1. Analysis of the status of the task and publications

A modern passenger or transport aircraft, as a complex technical system, comprises the following main subsystems: airframe elements, power plant, systems, equipment and control [3, 4]. In turn, the airframe structure of the aircraft includes the wing (including the pressurization of the fuel compartments), fuselage (including the pressurization of the compartments), empennage (including forks and washers) and landing gear (including the flaps and fairings). The power plant, with a turbojet engine or a turbojet bypass (three-circuit) engine, consists of the engines (main and auxiliary), engine systems and engine installation components, which include engine nacelles with air intakes, air channels and jet nozzles (if the engine is not structurally connected to the fuselage); pylons; cowlings; motors and attachment points [5].

Ensuring full interoperability of all subsystems is a complex task and requires comprehensive, systematic research. From the point of view of achieving the necessary flight characteristics, a modern passenger or transport aircraft, as a complex technical system, can be divided into two subsystems according to the complexity of the physical processes that occur in flight – the propulsion system and the airframe [6]. Since it is these two subsystems that largely determine an aircraft's performance characteristics, they will be the primary focus of this study. For the power plant, we will only consider the input device, the engine and the output device. For the airframe, we will consider the combination of fuselage, wing and empennage.

At present, the main developers and manufacturers of aircraft engines are paying increased attention to the creation of hybrid power plants (HPPs), which combine a heat engine (piston or gas turbine) and an electric motor [7, 8]. This combination can significantly increase the fuel efficiency of an aircraft, reduce harmful emissions and increase the efficiency of operation. The development of HPPs is expected to be propelled by significant leaps forward in related technologies, including electrical machines, chemical energy sources and high-power-density power electronics with reduced weight and compact dimensions [9, 10]. Concurrently, efforts are being made in complementary industries – most notably, exploring the possibility of using biofuel for gas turbine engines, which has the potential to radically reduce harmful emissions.

The transition to pure electric traction for passenger aircraft offers a number of advantages, including the following:

1. no more problems with multiple engine cycles,
2. reduced maintenance for fixed aircraft systems,
3. the possibility of replacing battery packs during stopovers,
4. significant reduction in external and internal noise levels,
5. no pollution during the flight.

The development of HPPs and their integration into aircraft for various purposes is currently one of the most significant trends in the aircraft engine market: combining a gas turbine engine and an electric motor can partially solve the main

challenges of modern aviation. Global experience shows that almost all major PP manufacturers for aviation are working on the creation of HPP to one degree or another. Pratt & Whitney [11], for instance, is implementing technologies to reduce harmful emissions into the atmosphere based on innovations in the design of control systems. At the same time, significant fuel savings are expected, estimated at up to 20% if the HPP is integrated into regional passenger and transport aircraft.

Collins Aerospace, in turn, is also breaking new ground in aircraft electrification, opening up new possibilities for design optimization. It has produced the first prototype 500KW electric motor for Hybrid Air Vehicles' Airlander 10 aircraft. This electric motor as part of a family of electric motors that can be scaled up or down to meet the needs of potential applications across multiple aircraft segments [12]. New sustainable electric propulsion technologies will advance aviation industry's efforts to reach net-zero carbon emissions by 2050. Collins Aerospace is also designing a 1 megawatt electric motor and motor controller for Pratt & Whitney Canada's (P&WC) regional hybrid-electric flight demonstrator. The two motors are part of Collins' technology roadmap for the development of a family of scalable electric motors for various hybrid-electric and all-electric applications [12].

United Technologies Corporation is also developing hybrid aircraft engines and installing them on various aircraft. In particular, the American corporation has presented a demonstrator of the Dash 8 light turboprop aircraft of the Canadian company Bombardier, which has a 2 MW HPP instead of one of the engines. Currently undergoing tests, this HPP-equipped aircraft will carry from 30 to 50 passengers over distances of 200–250 nautical miles (370–463 km) within one hour.

Rolls-Royce is testing components of its own HPP based on the AE2100. Its total capacity is 2.5 MW. The British company has repeatedly announced its intention to significantly reduce emissions by 2030. Meanwhile the French conglomerate Safran [13] is actively developing HPP for commercial aircraft. The company projects that these power plants will dominate its order book by the late 2040s or early 2050s. General Electric is also making notable progress with its TriFan HPP, designed for light passenger and transport aircraft. Its capacity will be about 1 MW, with maximum power of about 1,400 hp. When installed on the company's Denali light aircraft, the Cessna Catalyst will be capable of transporting up to 4 people over distances of up to 3,000 km at speeds of up to 527 km/h. Work is currently in the active stage, with a finished technology demonstrator of the HPP expected by the early 2030s.

As is well known, energy storage is a critical component for use on an electric aircraft. Five main parameters for evaluating suitability characteristics have been identified: specific energy or gravimetric energy density (nominal energy of the battery per unit mass, Wh/kg), volumetric energy density (nominal energy of the battery per unit volume, Wh/L), specific power (maximum available power per unit mass, W/kg) and number of cycles (number of charge/discharge cycles that the battery can undergo) [14].

Significant scientific, technical and experimental research on aircraft with hydrogen control system continues to be ongoing worldwide [15, 16]. Projects such as the H2FLY and HY4 aircraft have demonstrated the feasibility of using onboard hydrogen as a fuel source. The potential of hydrogen for future air mobility is enormous: in the coming years, hydrogen powertrain systems are expected to be able to power several subsystems for long range, zero emissions and a low-noise engine.

The papers [17, 18] provide an overview of the current state of civil transport aviation, starting with the analysis of electrical technologies for use in aviation and ending with the study of current proposals for conceptual designs of both short- and medium-haul and regional aircraft. They detail the potentials and limitations of the integration of the hybrid-electric propulsion system, proposing realistic targets for the design of the proposed aircraft technology for the next decade.

Article [19] offers a conceptual analysis of the limitations associated with the development and integration of a hybrid-electric propulsion system on regional transport aircraft, including a feasibility study of this innovative aircraft concept. Hybrid-electric aircraft have garnered interest in aeronautical research because they have the potential to reduce fuel consumption and therefore associated greenhouse gas emissions. However, the development of such aircraft configurations, while adhering to constraints arising from technological and/or operational aspects, may lead to an analysis of concepts that are unlikely to come to fruition.

The design parameters for a hybrid-electric control system are set in the process of sizing the installation. The parametric description of a dual-energy propulsion system requires the establishment of two fundamental algebraic parameters, namely the degree of hybridization for power (H_P) and the degree of hybridization for energy (H_E). The procedure for determining these parameters is given in [9]. The synergy between the qualities of a conventional and all-electric aircraft leads to the best integration of the control system with the stored energy source (battery) and fuel source (conventional engine). The degree of hybridization (DOH) expresses the percentage of total power required for the aircraft that comes from the electrical system [8]. The degree of hybridization most used in the literature is for energy (H_E) and power (H_P) [20], defined as:

$$H_P = \frac{P_{electric}}{P_{total}} = S; \quad H_E = \frac{E_{electric}}{E_{total}} = \psi.$$

One more parameter is introduced: the input power factor Φ [20]. The coefficient is defined as the total power of the electric motor $E_{EM\ total}$ for the entire flight cycle in relation to the total power on the shaft $E_{shaft\ total}$ for the entire flight cycle:

$$\Phi = E_{EM\ total} / E_{shaft\ total}.$$

The $L_{\max}$ value is also determined, which represents the maximum range of the aircraft with the electrical component of the control system. The parameter value can be obtained if the aircraft is flying at a constant altitude and at a constant speed (cruising section of the flight):

$$L_{\max} = \frac{L}{D} \cdot \frac{1}{g} \cdot \frac{m_{bat}}{MTOM} \cdot E_{bat} \cdot \eta_{total}.$$

The flight range of an aircraft depends on the ratio of lift to aerodynamic drag (L/D), battery mass (m_{bat}), maximum take-off mass of the aircraft ($MTOM$), specific energy of the battery at the package level (E_{bat}), and overall energy conversion efficiency (η_{total}). The value g represents the acceleration of gravity and is a constant.

Based on the review of scientific and technical information on the determination of the main indicators and criteria for the optimization of the gas control system with electric motors and FC, as part of a passenger aircraft, the following indicators are used in this study:

- the degree of energy hybridization for HPP:

$$DOH = \frac{E_{FC}}{E_{FC} + E_{jet\ fuel}},$$

where E_{FC} is the energy supplied from the FC system, W;

$E_{jet\ fuel}$ is the energy supplied from the combustion of fuel in the combustion chamber, W.

- the Payload Range Energy Efficiency ($PREE$):

$$PREE = \frac{W_{PL} \cdot R}{E_{flight}},$$

where $E_{flight} = E_{taxi\ out} = E_{TO} + E_{climb} + E_{cruise} + E_{descent} + E_{landing} + E_{taxi\ in}$ is the amount of energy consumed by the HPP during the flight cycle of the aircraft, W;

W_{PL} is the payload weight, kg;

R is the aircraft flight range, km.

- the Technological Readiness Level (TRL).
- the performance characteristics for regional aircraft: Maximum Payload Weight / Maximum Take-off Weight ($MTOW$);
- the economic characteristics of the aircraft: fuel consumption per flight cycle $FCons_{flight\ cycle}$ and the cost of 1 hour of flight $C_{hour/flight}$;
- the environmental characteristics of aircraft: the emission index (EI) and estimated CO₂ emission indicator, which will be adapted for schemes using hydrogen:

$$CO_2 = \frac{(1/SAR)_{AVG}}{(RGF)^{0.24}}, kg/km,$$

Where $(1/SAR)_{AVG}$ is the average value of the specific flight range of the aircraft; $(RGF)^{0.24}$ is the dimensionless geometric coefficient, which is based on determining the size of the fuselage reduced to 1 m².

While these indicators are essential for optimization, they often require detailed and accurate data, which is not always available during the early stages of development (aircraft concept selection). This limitation highlights the need for an alternative indicator that measures the degree of integration of subsystem characteristics at the conceptual design phase. Such an indicator would enable effective assessment and optimization even when detailed information is unavailable.

1.2. Purpose of the work

The purpose of this work is to develop an “integration index” as an indicator quantifying the degree of integration of the characteristics of aircraft subsystems based on its parametric representation. This integration index will make it possible to determine the options for design technical solutions for the PP as part of the aircraft at the preliminary stages of design. This will show the level of feasibility of the design indicators that meet the terms of reference for the aircraft.

1.3. Task Statement

The main tasks of this study are as follows:

- to analyze indicators and criteria for assessing the operational characteristics of a transport or passenger aircraft;
- to develop and propose an indicator of the degree of integration of the characteristics of aircraft subsystems – the “integration index”.

2. RESEARCH METHODS

To address the set tasks, this study employs the method of system engineering, the method of expert assessments, the method of assessing the level of technical perfection of aviation equipment objects (AEO) and the retrospective method. These methods made it possible to develop and analyze the integration indicator, as well as to obtain generalized equations of dependencies of the parameters of the workflow and characteristics of the control system with turbojet engines with minimal information about the design.

3. RESEARCH RESULTS

3.1. Rationale for the Use of Basic Indicators and Criteria for Aircraft Performance Assessment

The introduction of hybrid-electric technology has dramatically opened up the design space for new aircraft designs by broadening the range of combinatorial options at the aircraft level. This expansion has the potential to shift the current paradigm of aircraft design [21]. However, hybrid-electric technology is still in the experimental phase. An additional challenge in the application of hybrid electric technology is the possible synergistic implications when combined with other technologies, such as distributed propulsion, through a more integrated airframe, control and other aircraft systems interface [22].

For the purposes of comparison, the criteria (indicators) of technical excellence should meet several key requirements:

- Focus on essential properties: The criteria should identify and evaluate the most important characteristics of the aviation equipment object (AEO).
- Comparability: The criteria should allow for comparisons between objects of the same type and, if necessary, objects of different types.
- Simplicity: The criteria should remain straightforward to ensure usability.

The methods of comparative evaluation, which utilize specific criteria characterizing the level of technical refinement of aircraft, are the most widely used [3, 23, 24]. These methods can be roughly divided into two main types:

- Methods that use criteria that depend on only one property or measure. In this case, the criterion is the indicator itself. The method is reduced to a sequential comparison of two or more products, one of which is an analogue of two (or more) others for each pre-selected indicator;
- Methods that use criteria that include several properties or indicators that characterize all the basic properties of a product.

For most aircraft, a primary requirement is the ability to transport cargo over a specified distance with minimal energy expenditure. A critical indicator of an engine's fuel efficiency is its specific fuel consumption. To evaluate the suitability of a specific engine for an aircraft, it is essential to analyze both the engine's characteristics and the aircraft's performance metrics, considering factors such as required thrust, mass, and the geometric and aerodynamic properties of the airframe components:

$$q_{kilometer} = \frac{F \times TSFC}{V},$$

where F is the thrust, N;

$TSFC$ – the thrust-specific fuel consumption, kg/(N×hour);

$F \times TSFC$ – the hourly fuel consumption, kg/hour;
 V – the flight speed, km/hour.

The relative value of kilometer fuel consumption, expressed per kilogram of the aircraft's flight weight, can also be used:

$$\bar{q}_{kilometer} = \frac{F \times TSFC}{V \times m_{A/C}},$$

where $m_{A/C}$ is aircraft flight weight, kg.

More advanced criteria for optimality combine a variety of aircraft flight data into a single function. Of the criteria of this type, the value of the relative hourly productivity of the aircraft is used to evaluate transport aircraft:

$$\overline{Prod} = \frac{L_{pract} \times m_{payload}}{t_{flight} \times m_{T/O}} = V_{cruising} \cdot \bar{m}_{commercial},$$

where L_{pract} – practical flight range, km;
 $m_{payload}$ – payload mass, kg;
 $\bar{m}_{commercial}$ – commercial mass, kg;
 t_{flight} – flight duration, hour;
 $m_{T/O}$ – take-off weight of the aircraft, kg;
 $V_{cruising}$ – cruising speed, m/s.

A well-grounded judgment about the technical excellence of the aircraft in question can be made with the help of criteria based on economic indicators [3, 25]. One of the most common indicators for evaluating transport aircraft is the discounted costs:

$$C_{discount} = C_{transport} + C_{capital\ investments},$$

where $C_{transport}$ – the cost of transportation of commercial loads, USD;
 $C_{capital\ investments}$ – capital investments, which include the cost of operating the aircraft for one flight hour, USD.

When analyzing the efficiency of the use of engines on aircraft, the value that is the inverse of the relative kilometer consumption, that is, the conditional range, is used:

$$L_{conditional} = \frac{K_{A/C\ max} \times V}{SFC},$$

where $K_{A/C\ max}$ – maximum aerodynamic quality of the aircraft;
 SFC – specific fuel consumption, kg/(N×hour).

However, this criterion does not consider several very important relationships, including the effect of the operating process parameters and the size of the engine on its mass.

The theoretical flight range of the aircraft is determined under the condition of a constant speed V , a constant aerodynamic quality of the airframe $K=C_L/C_D$ and full fuel consumption in cruising flight, excluding acceleration, climb and descent sections:

$$L_{flight} = \frac{K}{g} \cdot H_u \cdot \eta_0 \cdot \bar{F}_{effective} \cdot \ln \frac{1}{\bar{m}_{airframe} + \bar{m}_{payload} + \bar{m}_{equipment} + \bar{m}_{control\ system} + \bar{m}_{fuel} + \bar{m}_{PP} + k_{PP} \cdot \mu_{T/O} \cdot \gamma_{engine}}$$

where $\bar{m}_{airframe}$, $\bar{m}_{payload}$, $\bar{m}_{fuel}$, $\bar{m}_{PP}$, $\bar{m}_{equipment}$, $\bar{m}_{control\ system}$ are the weight of airframe, payload, fuel, power plant, crew, equipment and weapons, and technical control systems, respectively;

k_{PP} – the coefficient of increase in the mass of the PP in comparison with the mass of the engine;

$\mu_{T/O}$ – the take-off thrust-to-weight ratio of the aircraft;

γ_{engine} – the specific gravity of the engine;

$\bar{F}_{effective}$ – the coefficient of relative decrease in the effective thrust of the engine due to the external resistance of the PP;

η_0 – the full engine efficiency

H_u – the calorific value of the fuel.

This expression combines separate indicators of the refinement of the aviation control system as a thermal engine, propulsion system and mechanical structure, which is characterized by dimensions and weight.

At present, the following parameters and characteristics are mainly identified as the desired values in solving the problem of matching the characteristics of the PP and the airframe:

1. The geometrical dimensions of the airframe, which are characterized by the wing area S_{wing} . The concept of specific load on the wing $G_{A/C}/S_{wing}$ is used.
2. The geometrical dimensions of the PP, which are characterized by the total inlet area S_{inlet} or the relative size of the PP S_{inlet}/S_{wing} . Sometimes the thrust-to-weight ratio of the $F_{T/O}/G_{A/C}$ aircraft is used.
3. The aircraft flight mode.
4. The operating mode of the PP, which is characterized by the thrust of the engine F_N and the control program of the PP elements (air intake, engine and nozzle).

With the help of these parameters, it is possible to express the aerodynamic, mass and flight characteristics of passenger or transport aircraft. In addition, the task of harmonizing the characteristics of the subsystems of a passenger or transport aircraft is to obtain the maximum (or minimum) of a certain target function – a coordination indicator that allows the degree of refinement of the aircraft to be judged.

Nevertheless, the choice of the main coordination indicator is a difficult task, since it is not always possible to reduce the entire variety of parameters and characteristics of the PP and airframe of the aircraft to one or at least several indicators. The most well-grounded judgment about the technical refinement of the aircraft in question can be made with the help of criteria based on the use of complex indicators of the technical excellence of its subsystems. As a rule, when the PP is integrated into the airframe, new integrative properties of the aircraft appear, which lead its flight performance characteristics to differ from the expected ones.

In addition, addressing the problem of the integration of the PP and the airframe of the aircraft under conditions of uncertainty of the initial information on the engine requires that the possible uncertainty of information on the airframe of the aircraft [26] also be taken into account, since changes in the process of creating the appearance of the aircraft will lead to changes in the parametric appearance of the engine and its operating conditions.

Thus, the development of a comprehensive integration index, gauging the degree of integration of aircraft subsystems, would make it possible to evaluate the overall effectiveness of the PP within the aircraft system and allow for the determination of applicable operational ranges

3.2. Development and substantiation of the “integration index”

The integration of control system subsystems with the airframe of passenger or transport aircraft is traditionally addressed through the alignment of individual control system and airframe indicators, based on the design requirements for the aircraft. However, as technical systems become increasingly complex – both for the aircraft as a whole and for their control systems – this approach falls short. It often fails to account for emergent integration properties, which necessitate substantial modifications during testing and operation phases. This process not only incurs significant public expenditure but also risks failing to achieve the desired performance outcomes for new or modernized aircraft.

In light of this, an analysis of the stages of integration of aircraft subsystems was carried out and their main parameters, indicators and characteristics were determined. The following stages of integration were distinguished:

- parametric integration, when the technical appearance of the aircraft being created is determined at the stage of selection of individual characteristics and indicators;
- criteria-based integration, when on the basis of the calculated values of complex indicators and criteria, the overall degree of compliance of the airframe and its PP is assessed, and the expected integrative properties can be predicted;
- constructive integration, when the system of design and layout solutions is evaluated, ensuring the greatest compliance of the aircraft characteristics determined at the stage of parametric and criterion integration with the actual performance characteristics;

- technological integration, when the system of technological processes is evaluated, ensuring the adequacy of manufactured products to the adopted design and layout solutions.

Of these, the stage of parametric integration is of particular interest, since it has the greatest impact on determining the flight performance of an aircraft as a complex technical system at the stage of preliminary development [27].

To study the parameters of the PP in order to identify the general patterns of their change, it is necessary, along with a set of specific flight and technical criteria for evaluating the aircraft, to have a single generalizing criterion that characterizes the effectiveness of the PP in the aircraft system, which would allow optimal solutions to be found in a general form. The variety of criteria is explained by the fact that certain requirements are imposed on different aircraft in each specific case, which are put forward by the customer. To take into account all these requirements as fully as possible, such a variety of criteria is necessary. For each specific project, a specific combination of criteria and constraints can be selected.

However, the given indicators and criteria do not fully consider the degree of technical refinement of aircraft design and layout solutions based on traction, aerodynamic and geometric characteristics. To assess integrative properties, it is necessary to have such an indicator able to consider the features of traction, aerodynamic and geometric characteristics in one design and layout scheme of the aircraft. The main factor that affects the integrative properties of the aircraft is the aerodynamic drag of the PP and airframe elements. The force of external aerodynamic drag of the surfaces of the PP, which are streamlined by the incoming air flow, can be determined using the coefficient C_D related to the area of the midsection S_{midel} of the PP and to the velocity head of the incoming flow [28].

The friction and pressure resistance coefficients depend on the M number, the Re number, as well as the pressure drop across the nozzle cut and the shape of the fairing. All these parameters are determined experimentally or with the help of mathematical modeling of gas and airflows. To assess the thrust and geometric characteristics of the aircraft, we introduce the ratio $\left(\frac{F_{engine}}{G_{A/C}}\right)/S_{bearing\ surface}$ as a value that characterizes the thrust capabilities of the PP per 1 m² of the aircraft bearing surface on which this PP is installed. Taking into account the aerodynamic and geometrical characteristics, we use the ratio $C_{D\ nacelle}/S_{midel}$ as a value that characterizes the aerodynamic resistivity of the engine nacelle as part of the airframe.

Thus, in order to substantiate the integrative properties of the aircraft, it is necessary to distinguish the thrust of the engine (or $C_{D\ nacelle}/S_{midel}$), which is accounted for by the resistivity of the aircraft related to 1 m² of the aircraft's bearing surface. As a result, we get an integration indicator:

$$\Pi_{integration} = \frac{\left(\frac{F_{engine}}{G_{A/C}} \right)}{S_{bearing\ surface}} \bigg/ \frac{C_{D\ nacelle}}{S_{midel}} = \frac{\left(\frac{F_{engine}}{G_{A/C}} \right) \cdot S_{midel}}{S_{bearing\ surface} \cdot C_{D\ nacelle}}$$

where F_{engine} – engine thrust, N;

$G_{A/C}$ – aircraft weight, kg;

S_{midel} – the midsection area of the airframe, sq.m.;

$S_{bearing\ surface}$ – the area of the airframe bearing surface, sq.m.;

$C_{D\ nacelle}$ – aerodynamic drag coefficient of the engine nacelle.

The physical essence of the developed indicator of the level of integration involves quantifying the integrative properties of the aircraft, considering traction, aerodynamic and geometric characteristics. The developed indicator is applied to perform a comparative assessment of transport and passenger aircraft [29]. The aircraft were selected with a different number of engines and were divided into 4 groups: aircraft with 4 turbojets; aircraft with 2 turbofan engines; aircraft with 2 turbofan engines and 1 turbojet engine; aircraft with 4 turbofan engines.

Based on the given parameters of the airframe and its PP, the integration index was calculated. The dependence of this integration index on the characteristics of the engine and airframe of the aircraft is shown in Figs. 1-4, indicating that the proposed integration index is sensitive to design and layout solutions, namely, to the number of engines on the aircraft. From the analysis of the above dependencies, we can conclude that characteristic ranges of integration index values can be distinguished for all the aircraft under study (Table 1). For example, for aircraft with 4 turbojets, $0.39 \leq \Pi_{integration} \leq 0.65$; with 2 turbofan engines $3.36 \leq \Pi_{integration} \leq 6.69$; with 2 turbofan engines and 1 turbojet engine $2.12 \leq \Pi_{integration} \leq 3.0$; with 4 turbofan engines $11.11 \leq \Pi_{integration} \leq 2.02$. From the obtained dependencies of aerodynamic quality on the geometrical parameters of the aircraft, for all design and layout solutions of aircraft with a different number of engines, the presence of a minimum value of the midsection area of the aircraft with a characteristic value of the maximum aerodynamic quality is noted.

Of interest is the fact that with the placement of bypass engines on the aircraft, the maximum aerodynamic quality of the aircraft $K_{A/C}$ is almost in the same range. So, for aircraft with 4 turbojets, $4 \leq K_{A/C} \leq 11$; for aircraft with 2 turbofan engines $12 \leq K_{A/C} \leq 17$; for aircraft with 2 turbofan engines and 1 turbojet engine $13 \leq K_{A/C} \leq 17$; for aircraft with 4 turbofan engines $14 \leq K_{A/C} \leq 22$.

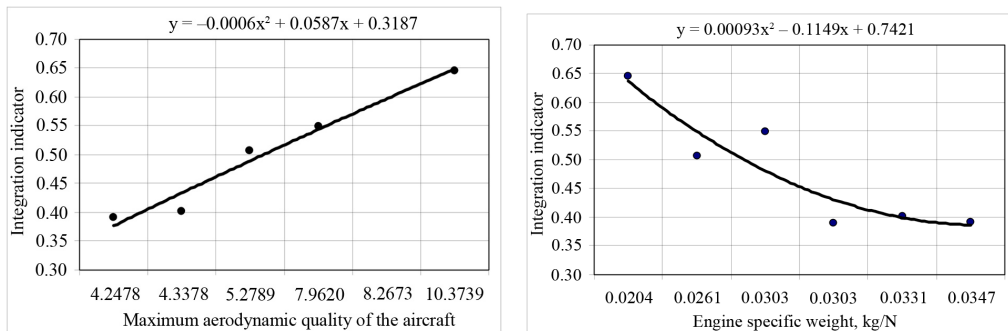


Fig. 1. Dependence of the integration index on the characteristics of the engine and aircraft (with 4 turbojets).

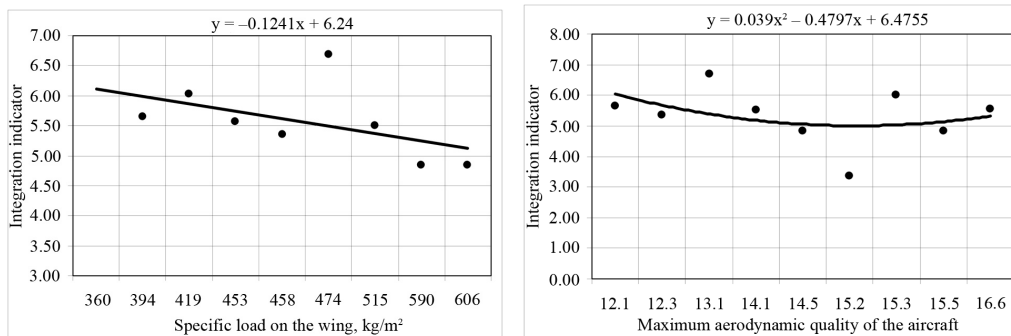


Fig. 2. Dependence of the integration index on the characteristics of the engine and aircraft (with 2 turbofan engines).

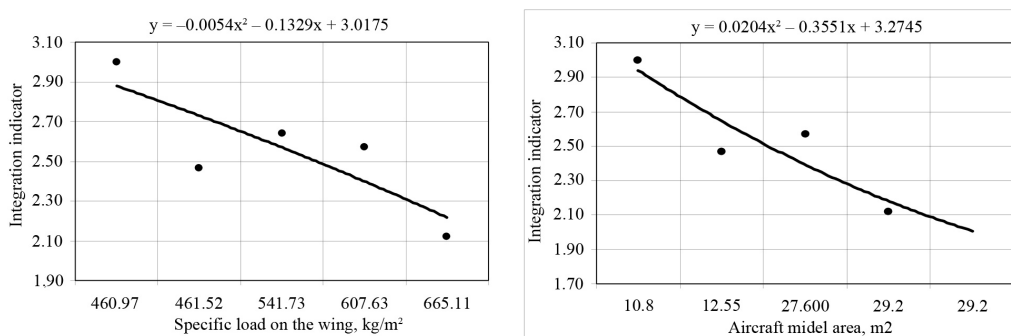


Fig. 3. Dependence of the integration index on the characteristics of the engine and aircraft (with 3 turbofan engines).

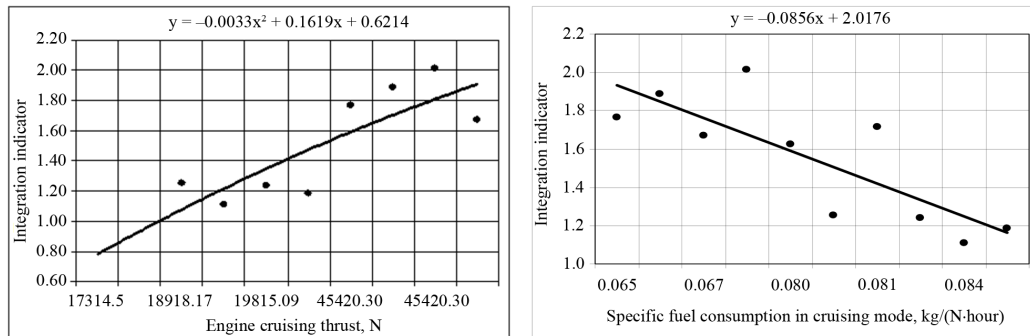


Fig. 4. Dependence of the integration index on the characteristics of the engine and aircraft (with 4 turbofan engines).

Table 1. Ranges of variance in the values of the integration index.

Number of aircraft under study	Number and type of engine	$\Pi_{integration}$	$K_{A/C}$	S_{midel}, m^2
6	4 turbojets	0.4...0.7	4...11	7.5...12.8
9	2 turbofan	3.4...6.7	12...17	8...25
5	2 turbofan + 1 turbojet	2.1...3.0	13...17	10.8...30
10	4 turbofan	1.1...2.0	14...22	12...40

In general, the proposed integration index is of a general nature and takes into account the main characteristics of the power plant and airframe of the aircraft. This indicator can be used both to directly determine the characteristics of the aircraft, and vice versa, by setting its value, it is possible to determine the parameters of the aircraft as a single technical system.

4. DISCUSSION OF THE RESULTS

The calculated values of the integration index for various groups of aircraft have facilitated the derivation of generalized equations representing the dependencies of the integration index on the parameters and characteristics of the power plant (PP) and airframe. The equations of dependence of the integration index on the parameters and characteristics of the airframe and PP represent surfaces in multidimensional space [30]. Since in this space there is a best value for each parameter and characteristic, it is possible to imagine a rational surface that describes a rational range of parameters and characteristics of the aircraft.

The results demonstrate that the developed integration index is sensitive to the number of power plants on the aircraft. This sensitivity enables the assessment of the degree (depth) of integration between the airframe and control system during

the preliminary development stages. The indicator effectively characterizes the technical sophistication of the aircraft’s design and layout, treating it as a unified technical system.

Furthermore, the proposed integration index can also be used to address inverse problems. For instance, given a predefined value of the integration index within a specified range of airframe characteristics, it is possible to deduce the parameters and characteristics of the PP engine. This capability enhances the utility of the indicator in the early design phases, guiding decision-making for both airframe and PP optimization.

5. CONCLUSIONS

This study has developed and proposed an “integration index” that quantifies the integrative properties of an aircraft, considering its thrust, aerodynamic, and geometric characteristics, as well as design and layout solutions. The indicator is sensitive to the number of control systems (e.g., power plants) on the aircraft and enables a quantitative evaluation of subsystem integration during preliminary development stages. The generalized equations derived from this study reveal the dependence of the integration index on the parameters and characteristics of the airframe and its control system. These equations provide insights into the influence of subsystems on the performance of the aircraft as a complex technical system.

When designing hybrid-electric aircraft, it is critical to compare their characteristics with conventional aircraft designed for the same flight profiles. Failing to account for this can result in overestimations of the advantages of hybrid-electric propulsion configurations. A key consideration for hybrid-electric aircraft is the strategy for managing electrical and thermal energy throughout the flight cycle.

Key factors in designing hybrid-electric aircraft revolve around three interconnected aspects: the degree of electrification, the operating strategy, and the power management strategy. The degree of electrification plays a fundamental role in determining the size and capacity of control system components, directly influencing the aircraft’s design and integration. Meanwhile, the operating strategy governs fuel consumption by determining how power is distributed between different energy sources throughout the flight cycle, shaping the overall efficiency and performance. Lastly, the power management strategy defines how power is allocated between the propulsion system and other subsystems, guided by the assigned flight profile and size constraints of the subsystems. This strategy has a critical impact on component design and their integration within the aircraft.

By combining the integration index with optimized power management strategies, designers can ensure hybrid-electric aircraft meet the required balance of performance, efficiency, and subsystem integration. This approach allows adherence to the specific constraints imposed by the intended flight profile, ensuring a well-rounded and efficient design.

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