J. Appl. Comput. Mech., 8(4) (2022) 1307-1314
DOI: 10.22055/jacm.2022.39741.3455

ISSN: 2383-4536
jacm.scu.ac.ir

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University of Ahvaz

Journal of
Applied and Computational Mechanics

Research Paper

Moment-Inertial Factor as a Criterion for Assessing the Dimension of an Aircraft

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Received January 12 2022; Revised February 18 2022; Accepted for publication March 14 2022.
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Abstract. The study aims to compare the characteristics of the moment-inertial schemes of two aircrafts – a mainline aircraft of a normal aerodynamic scheme and an aircraft made according to the flying wing scheme, to improve their flight performance. The study uses the method of successive approximations using relative masses (when determining m0), the formula of A. Mozhaisky, an artificial method consisting of the layout of the aircraft oriented to the virtual center of mass. Design studies at the modern level of scientific and technical development have confirmed the relevance of using the proposed methods of forming a moment-inertial appearance for promising long-haul aircraft of large passenger capacity.

Keywords: Linear dimension, airplane volume, square-cube law, load-range diagram, fifth-degree.

1. Introduction

A little more than a century separates us from the first flight of the Wright brothers. During this period, aircraft began to fly faster and farther than birds. With the development of aviation, people have learned to fly non-stop around the globe, take off vertically, and land where necessary. But everything comes with a price. In aviation, this price is the mass, or weight, which is a more commonly used term. This criterion is simple, straightforward, and convenient. Weight equivalents can be applied to both runway length and aerodynamic quality (Fig. 1). And when all the masses are summed up, then the payload mass first disappears from the limit, and then the flight range begins to decrease. When these two curves intersect, the design degenerates. The Figure below 2 presents it as point A.

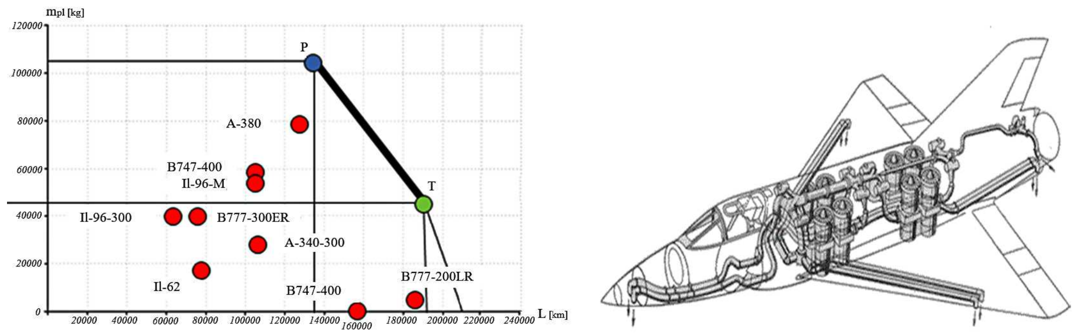


Fig. 1. Chart of payload mass – flight range depending on the takeoff weight of the aircraft

Published online: March 25 2022

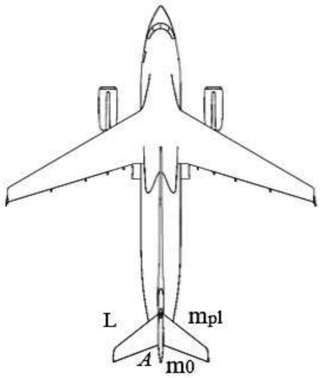


Fig. 2. Intersection of curves L and m_{pl}

The takeoff weight of an aircraft can be expressed as:

$$m_0 = m_{p.w.} + m_{eq} + m_{c.eq.} + m_{p.p.} + m_F + m_S \quad (1)$$

Here (using the example of the main plane):

$m_{p.w.}$ is a mass of payload (target, commercial) weight (passengers, their baggage, cargo, and mail) that the aircraft delivers to its destination;

m_{eq} is the mass of equipment that provides certain conditions for the comfort of the payload on board. The mass of equipment is not only chairs, kitchens and meals, air conditioning systems, etc., but also the mass of the crew and flight personnel (flight attendants) who serve passengers. Notably, m_{eq} significantly depends on the operating and application conditions set by the Technical Requirements Specification (TRS). It is assumed that the aircraft will be operated from elementary prepared airfields; the equipment should include built-in ladders and an auxiliary power unit that ensures the operation of the air conditioning system while the aircraft is parked and preparing it for flight. The same decision can be made even at high-class airports, for the independence of the aircraft from airfield facilities;

$m_{c.eq.}$ – weight of control equipment that ensures the operation of the aircraft in the given conditions (flight and navigation equipment, air navigation system and power equipment for the operation of all systems). The composition and weight of control equipment also significantly depend on the operating conditions and use of the aircraft, the composition and capabilities of ground equipment that provides navigation in the area of the destination airport and along the entire flight route;

$m_{p.p.}$ – power unit weight (engine, fuel systems), providing the necessary flight speed to deliver the payload in time T to a distance L;

m_F – mass of fuel on board;

m_S – aircraft structure mass (fuselage, wing, empennage, landing gear, rudder and aileron control systems). The aircraft structure is the main component that unites all systems into a single complex that defines the appearance of the aircraft.

It is noteworthy that the take-off mass m_0 of the aircraft affects practically all the masses included in the equation of existence. There is a very strong and complex dependence between m_k and m_0. The greater the takeoff weight of the aircraft, the more material will obviously have to be spent to ensure the strength and rigidity of its structure, i.e., to make it heavier, and, accordingly, when the structure becomes heavier, the take-off weight of the aircraft increases. Thus, the equation of existence cannot be solved for m_0 in a finite form.

Increasing requirements for the characteristics of modern aviation technology have led to a broad search for new design solutions. Work by A.B. Avedian is devoted to the features of weight design and methods for calculating the moments of inertia of long-haul aircraft [1]. Works by O.S. Dolgov are devoted to the mutual coordination and integration of airframe elements and aircraft systems in the formation of the appearance of the original schemes [2-4]. O.A. Butusova analyzed the influence of external factors on the appearance of the aircraft control system [5-8]. The tasks of designing aircraft control systems are described in [9-14]. M.O. Kaptakov considers the issues of the aerodynamics of controls [15-17]. Yu.V. Ioni considered modern topical problems of control systems and power systems of long-haul aircraft [18]. The experience of research and design work, as well as the operation of aircraft, creates a scientific base and confirms the relevance of this study.

The aim of the study is to carry out a comparative analysis of the characteristics of the moment-inertial configurations of mainline aircraft of a normal aerodynamic configuration and an aircraft made according to the "flying wing" scheme to improve their flight performance. The main outcomes of the research:

- to consider the alternative options for the moment-inertial arrangement of the fuel, engines, and payload and their effect on the mass of the aircraft;
- to evaluate how the parameters of the moment-inertial layout affect the flight range.

2. Materials and Methods

To solve the equations, we will apply an artificial technique, which consists in carrying out the layout relative to the virtual centre of mass of the aircraft. Eliminating uncertainty about the position of the aircraft's center of gravity simplifies the location of nodes that have restrictions on their placement for the center of mass. These units include the chassis, wing, fuel tanks, etc. This circumstance introduces changes in the order and procedure for the layout of aircraft units and systems. The layout is conventionally divided into four stages:

Stage 1 – powertrain layout;
Stage 2 – the layout of units requiring open areas;
Stage 3 – the layout of the airframe units;
Stage 4 – layout of other units and systems.

Within each stage, constituting a closed cycle described by the equations of binding of aggregates, the coordinates of binding of these aggregates are determined. The equations are linked by layout procedures that solve a set of equations for the appearance of the aircraft. The dialectics of the development of design ideas at all stages, when engineers proceeded from the overall dimensions of the aircraft, made it possible to overcome the border, for example, a sound or thermal barrier. In a situation with a flight range, we observe the action of the “square-cube” law. The dimension of the aircraft cannot endlessly increase. The mass of the entire aircraft (*m*), depending on its volume (*V*), grows in proportion to the cube of the increase in linear dimensions (R^3) while maintaining geometric similarity, while the lift (*Y*), depending on the wing area (*S*), grows in proportion to the square of the linear dimensions (R^2). An increase in the mass of an aircraft, which outstrips the growth of lift, must inevitably limit the maximum increase in its linear dimensions.

Using foresight as a method for determining promising development trends, we can state that the use of profile laminating, composite and nanomaterials, hybrid and integral designs, additive technologies, etc., will contribute to weight reduction. But not one of these directions does not provide a radical correction of the situation. A bracket made using additive technologies can reduce its weight by 30%, but this is only 300 g. In terms of the entire aircraft, for thousands of structural parts, this is a significant gain, but there are limits to it. Somewhere additive technologies are not applicable due to the dimension of the aggregates.

3. Results and Discussion

In design practice, m0 is determined by the method of successive approximations using relative masses:

$$\overline{m}_{p.p.} = m_{p.p.} / m_0, \tag{2}$$

$$\overline{m}_F = m_F / m_0, \tag{3}$$

$$\overline{m}_S = m_S / m_0, \tag{4}$$

Therefore, the equation of existence is written in the following form in terms of the relative masses of nodes and systems of the aircraft:

$$1 = \overline{m}_{p.w.} + \overline{m}_{eq} + \overline{m}_{c.eq.} + \overline{m}_{p.p.} + \overline{m}_F + \overline{m}_S, \tag{5}$$

With $m_{p.w.}$, m_{eq}, $m_{c.eq}$ given in the TRS, i.e., with a known composition of equipment that ensures operation in the given conditions of the aircraft and the comfort of passengers on board, as a first approximation, the weight of the aircraft can be determined as:

$$m_0 = \frac{m_{p.w.} + m_{eq} + m_{c.eq.}}{1 - (\overline{m}_{p.p.} + \overline{m}_F + \overline{m}_S)}, \tag{6}$$

where: $m_{p.p.}$, m_F, m_S are the values of relative masses known from the design practice (statistics), which are quite stable for a certain type of aircraft and the level of their technical perfection, showing what percentage of the takeoff weight of the aircraft they are.

In the course of subsequent iterations (a more detailed study of the project), the values of the take-off mass and its components will be continuously refined in the case of a volumetric layout, when the aerodynamic scheme, taking into account the required operating range of the center of gravity, the volumes and relative position of the compartments for accommodating the payload and all aircraft systems are determined based on the selected shapes and sizes of the aircraft. For example, for an aircraft with vertical take-off and landing, to find the admissible vector of design parameters *X*, the system of the following equations is solved to correlate the appearance of the aircraft:

$$\begin{cases} \sum_j \overline{m}_j(x) - 1 = 0; \\ \sum_j m_j(x) * g - \sum_i (P_0^{XYZ})_i = 0; \\ \sum_j m_j(x) * g * R_j - \sum_i (P_0^{XYZ})_i * R_i = 0; \\ \sum_j m_j(x) * g * R_j^2 * \varepsilon_{XYZ} - \sum_i (P_0^{XYZ})_i * L_i = 0; \end{cases}, \tag{7}$$

where: $\vec{P}_i$ – force vector of the control body; m_j – mass of the *j*-th element of the aircraft; $\vec{g}$ – acceleration of gravity; $\vec{R}_i$ – radius vector of the *i*-th element of control systems; $\vec{R}_j$ – radius vector of the centre of mass of the *j*-th element of the aircraft; ε_{xyz} – angular acceleration; L_{xyz} – shoulder of the jet rudder. In the listed order, the equations providing the condition for the mass balance are given; energy balance condition; balancing condition; condition of controllability in pre-evolutionary flight modes.

The resulting system of equations is a system of four nonlinear equations for the parameters of linking the appearance of the aircraft, which are the radius vectors of the attachment points of aggregates and organs of power systems. The solution of such a system by traditional methods seems to be difficult, since the number of aggregates whose coordinates must be found is already at the i + 1 level $k > 103$, and the number of thrust vectors of energy systems is $n > 101$. To solve this system of equations, a set of procedures is used, which formed the basis of the proposed formal-heuristic method for forming the appearance of an aircraft with a "hard" infrastructural limitation on vertical takeoff and aircraft dimensions. The economic aspects of the design force to improve the design of the components and systems of the aircraft by reducing the relative weight of the empty equipped aircraft. The way to reduce the moments of inertia of the aircraft provides ample opportunities for reducing the cost of the thrust of the powerplant package for aircraft control. In general, the moments of inertia of the aircraft are calculated as follows:

$$\begin{cases} I_x = \int_m (y^2 + z^2) dm = \int_V (y^2 + z^2) \rho dV = \iiint_{xyz} (y^2 + z^2) \rho dx dy dz; \\ I_y = \int_m (x^2 + z^2) dm = \int_V (x^2 + z^2) \rho dV = \iiint_{xyz} (x^2 + z^2) \rho dx dy dz; \\ I_z = \int_m (y^2 + x^2) dm = \int_V (y^2 + x^2) \rho dV = \iiint_{xyz} (y^2 + x^2) \rho dx dy dz; \end{cases} \tag{8}$$

where: m, ρ, and V are the mass, density, and volume of the aircraft; x, y, z are coordinates of the centres of mass in the associated coordinate system of the aircraft of the decomposed aircraft elements, having a volume dV and a mass dm.

An analysis of the expressions shows that the moment of inertia is influenced only by the location of the masses relative to the axis and the shape of the body, and the radius of gyration can serve as a relative criterion for the rationality of the arrangement of aggregates in the location field:

$$r_{xyz} = \sqrt{\frac{I_{xyz}}{\sum_i m_i}}, \tag{9}$$

The formulas (1-14) of the moments of inertia of the aircraft completely or partially do not take into account the features of the aircraft layout. To make it convenient to take into account the influence of the arrangement of aircraft units on the value of the moment of inertia of expression in terms of Steiner's theorem, we will write as:

$$I_{1-1} = I_{0-0} + m * R_{1-0}^2, \tag{10}$$

The expression characterizes the radius vector and mass between the axes 1-1 and 0 -0 and through the moment of inertia of the body relative to its axis of inertia 0-0 through the moment of inertia of the body and the moment of inertia of the body relative to the axis 1-1. This expression shows the dependence of the moments of inertia of the aircraft on the arrangement of nodes and systems of the aircraft through the radius vector (distance). According to the square-cube law, a change in linear size affects mass to the third degree, the fifth degree of dependence of the moment of inertia on a change in linear size is determined by multiplying the mass by the square of the radius of rotation. Assuming that the target load corresponds to a single transport operation, we can assume that this criterion provides information about the amount of fuel required to complete the flight mission.

$$if \;\; (R\uparrow) \Rightarrow X_4 = \mathrm{Log}_R(I_{xyz}) = 5, \tag{11}$$

The fifth degree causes greater sensitivity of the function (Fig. 3). Changing the radius of gyration leads to an extremely harsh response from the feeder of the unit.

The degree of sensitivity of the placement function can be estimated using the moments of inertia, as well as their relationship to the required and available torque for control:

$$M_{av} = PL \tag{12}$$

$$M_{req} = I\varepsilon \tag{13}$$

In general, the available control torque in all three channels must exceed the required one. Graphic interpretation is presented in Fig. 4.

The available steering torque linearly depends on the arm to the control element and its area. The larger the shoulder, the smaller the area with an equal static moment for control, and it is not possible to remove the rudders indefinitely. The rudder layout is limited by the aerodynamic layout of the aircraft. But the required moment depends on the volumetric weight layout inside the washed surface of the aircraft, which is obtained as a result of the aerodynamic layout of the aircraft. Geometric-graphic interpretation of the graph is a contradiction between the image of a ball – a body with a minimum moment of inertia at equal volume, and an elongated spindle-shaped body corresponding to a body of minimum resistance (Fig. 5).

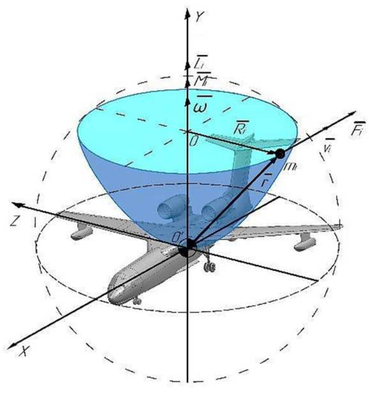


Fig. 3. Moment-inertial paraboloid of the aircraft

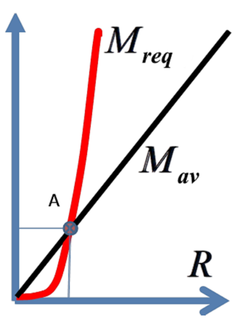


Fig. 4. The correlation of the required and available moments for aircraft control

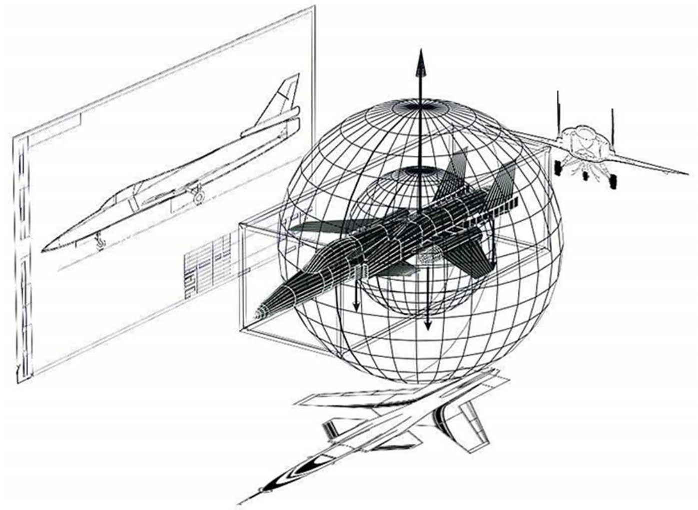


Fig. 5. The moment-inertial layout of the aircraft

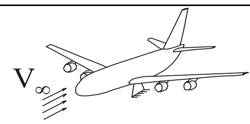
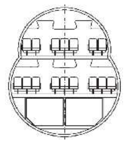
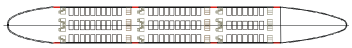
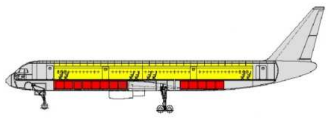
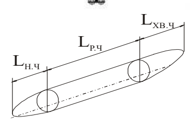
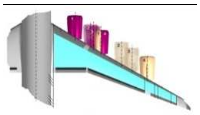
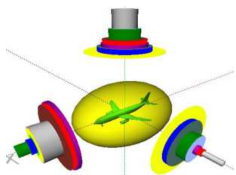
Translating the graphical view into an analytical interpretation, we write down the equation of the aircraft existence in relative moments of inertia:

$$1 = \sum_i \bar{I}_i. \tag{14}$$

where: $\bar{I}_i$ – inertia of the i-th element of aircraft.

The measure of inertia during translational motion is mass, and the measure of inertia during rotational motion is the moment of inertia. The higher the requirements for angular accelerations ε_{xyz}, the higher the role of the moment-inertial arrangement. This circumstance introduces changes in the order and procedure for the layout of aircraft units and systems, which is conventionally divided into several stages. In expanded form, this process can be represented as follows (Table 1) [2-8].

Table 1. Stages of the formation of the moment-inertial appearance of the aircraft

Layout stage	Influence on moment-inertial characteristics	
Aerodynamic		I_x I_z I_y
Requirements and limitations	u ∈ U	I_x I_z J_y
Identifying stackable sections based on the number of economy class passengers		I_z
Longitudinal deck layout		I_z
Cargo-passenger fuselage layout		I_z
Fuselage geometric parameters		I_z
The layout of the power plant and fuel tanks		I_x
Integral assessment of moment-inertial characteristics $I_y = f(I_x + I_z)$		I_x I_z I_y
Verification at the TT level	Aircraft = f(TT)	I_{xyz}

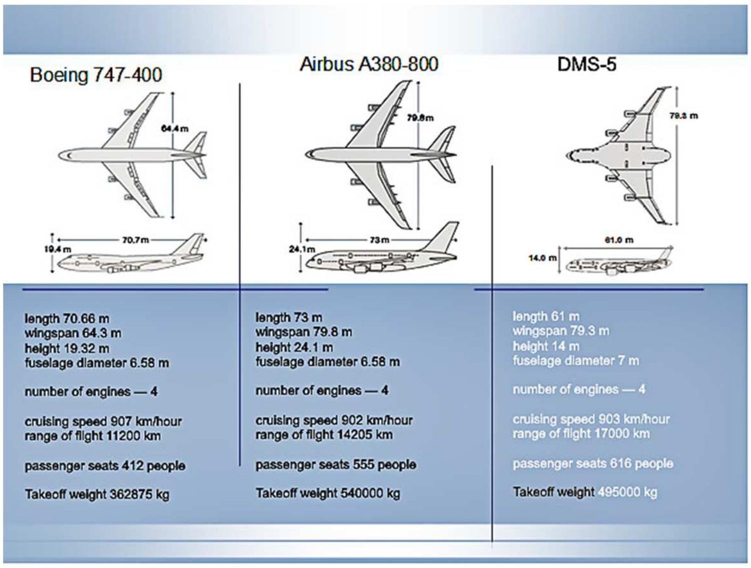


Fig. 6. Long-haul passenger aircraft

The binding coordinates of these aggregates are determined within each stage that makes up a closed cycle described by formal models of the aggregation binding equations. Shown in Fig. 6 are the characteristics of airplanes corresponding to these three characteristic flight ranges. It is noteworthy that all three aircrafts are designed to operate in the same aviation infrastructure, flying at the same speed, with the same type of propulsion system in four propulsion systems, and using kerosene as fuel.

The solution of the system of equations for the appearance of the aircraft becomes possible thanks to the layout procedure linking the equations. As part of the formation of the moment-inertial appearance of the aircraft, the stages of the layout of the target load, fuel tanks, and the power plant are inextricably linked, since they make the greatest contribution to the formation of moments of inertia, since quantitative values (in some configuration options up to 40% of the total moment of inertia relative to given axes) and from the point of view of quality – these devices have a certain freedom of movement of their center of mass, and can, by changing the parameters of the layout, conceptually change the moment-inertial types of the aircraft.

The alternative options for the moment-inertial arrangement of the fuel, engines, and payload and their effect on the mass of the aircraft were considered. Taken together, the results of this analysis served as the basis for studying the mutual influence of the relative mass of the fuselage, wing and parameters of the moment-inertial scheme in the form of the radii of inertia of passengers and the luggage compartment. This, in turn, made it possible to evaluate how the parameters of the moment-inertial layout affect the flight range.

As a result of the analysis, it was found that when comparing with the implemented projects, the data obtained as optima on the graphs of the areas of moment-inertial characteristics (their permissible values) allow increasing flight characteristics up to 7-8% by reducing and stabilizing the moment-inertial appearance during flight. The change in the influence of moment-inertial parameters on the appearance and flight performance of an aircraft with a change (increase) in the dimensions of the aircraft determines the revealed dependence of the flight range on the take-off mass at optimal values of the moments of inertia reflects. These studies confirm the relevance of research aimed at optimising the moment-inertial appearance for long-haul aircraft of large passenger capacity. Other aspects of improving the flight performance of aerospace systems are described in [19-33].

4. Conclusions

1. A comparative analysis of the characteristics of the moment-inertial configurations of mainline aircraft of a normal aerodynamic scheme and an aircraft made according to the "flying wing" scheme obtained as a result of a numerical experiment showed a clear advantage in the moment-inertial characteristics of an aircraft made according to the "flying wing" scheme.

2. In the moment-inertial form, many unconditional advantages have been revealed, such as more rational placement of fuel tanks, target load and power unit, which ensured an increase in aircraft mass up to 7-8% only due to a rational moment-inertial layout.

3. Design studies at the modern level of scientific and technical development have confirmed the relevance of using the proposed methods of forming a moment-inertial appearance for promising long-haul aircraft of large passenger capacity

4. Variations in the linear dimension of the aircraft affect the moment of inertia of the aircraft to the fifth degree.

Author Contributions

M.Yu. Kuprikov planned the scheme, initiated the project, and suggested the experiments; P.O. Polyakov conducted the experiments; N.M. Kuprikov analyzed the empirical results. The manuscript was written through the contribution of all authors. All authors discussed the results, reviewed, and approved the final version of the manuscript.

Acknowledgments

The study was performed with the financial support of the state project of the Ministry of Education and Science on the topic “Theoretical and experimental research in production and processing of advanced metal and composite materials based on aluminum and titanium alloys” FSFF-2020-0017.

Conflict of Interest

The authors don’t have any conflict of interests to declare.

Funding

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Data Availability Statements

The datasets generated and/or analyzed during the current study are available from the corresponding author on reasonable request.

Nomenclature

$m_{p.w.}$	Mass of payload (target, commercial) weight
m_{eq}	Mass of equipment
$m_{c.eq}$	Weight of control equipment
$m_{p.p}$	Power unit weight
m_j	Mass of the j-th element of the aircraft
$\vec{g}$	Acceleration of gravity
ε_{xyz}	Angular acceleration
L_{xyz}	Shoulder of the jet rudder
m_F	Mass of fuel on board
m_S	Aircraft structure mass
m_0	Takeoff weight of the aircraft
$\vec{P}_i$	Force vector of the control body
$\vec{R}_i$	Radius vector of the i-th element of control systems
$\vec{R}_j$	Radius vector of the centre of mass of the j-th element of the aircraft
$\bar{I}_i$	Inertia of the i-th element of aircraft

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How to cite this article: Kuprikov M.Yu., Polyakov P.O., Kuprikov N.M. Moment-Inertial Factor as a Criterion for Assessing the Dimension of an Aircraft, *J. Appl. Comput. Mech.*, 8(4), 2022, 1307–1314. https://doi.org/10.22055/jacm.2022.39741.3455