Load of the Reaction ZPL-20 Cannon 20 mm on L-159 ALCA Airplane Stability

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Abstract

The paper deals with the flow over the L-159 ALCA aircraft airfoils in subsonic regime. Authors have analyzed and assessed the effects of external loads on the aircraft structure during fire. In addition, the impact of the airborne cannon fire on the aircraft stability has been examined. Next, the results of calculations have been analyzed and changes in armament have been proposed. In proposing changes, safe use of cannon in combat has been considered. Moreover, changes also pertained to the aircraft tactical employment mainly at low speeds.

Keywords*:* Aerial Cannon ZPL-20, Aircraft L-159 ALCA, Numerical Calculations, Airfoil Flow, Subsonic Regime.

1. Introduction

High operational dependability of airplanes is of critical importance. The issue of operational dependability is dealt with in designing all types of aircraft. It is required to make air traffic safe and use aircraft efficiently. Low dependability increases the probability of failures. As faulty aircraft constructions (particularly in the primary system) cause crashes putting human lives in danger, dependability of aircraft must be given uttermost attention.

In most cases, the maximum operational dependability of aircraft is a costly option. Efficiency of airplanes is conditioned by the ratio between the payload and the weight of empty aircraft. Aircraft industry considers right and proper only the materials of relatively low weight, high strength and resistance against operational load.

In addition, combat aircraft are required to be combat-effective under any conditions, such as common combat situations (i.e. deliberate attacks) or emergency situations (i.e. unexpected attacks). The latter will test the qualities of both the pilot and the airplane in the first place. Airborne weapon systems must be capable of warding off attacks, even if the aircraft is damaged to some extent. Moreover, dependability and effectiveness of combat aircraft must be of the highest standards. Even the slightest failure of the weapon systems may be disastrous in military terms, and may incur damage to property and endanger human lives. Aircraft capabilities, such as flying, maneuvering and navigation must not be restrained the weapon system employment [1,6].

2. Flow over airfoils in subsonic regime

Generally, the flow over an airfoil is always meant the flow over a wing of indefinite span positioned perpendicularly to the air flow. The flow over the real wings of finite span comes very close to it, the slender the wings, the closer the flow approximates the general definition mentioned.

Geometric airfoil characteristics, angle of attack definition and aerodynamic characteristics at low air speed are shown in Fig. 1, 2 and 3. The airfoil lift and moment curves are virtually straight lines up to reaching the critical angle of attack value α_{krit} when the flow separation occurs and all characteristics change profoundly.

In subsonic regime, the speed over the entire airfoil is lower than the local velocity of sound. The flow over the airfoil is similar to that in an incompressible liquid, i.e. the changes in speed, pressure, density of the flowing air are continuous and steady.

The only difference is that the excess pressure and negative pressure over the airfoil are slightly higher than the ones corresponding with the respective flow pressure in an incompressible environment. Nevertheless, the excess pressure and negative pressure over the airfoil generate mainly lift force and a slightly increasing moment. The lift and moment coefficients may increase proportionally, compared to the values obtained in an incompressible environment, and can roughly be expressed by the following relations:

$$c_{ystl} = c_{ynestl} \frac{1}{\sqrt{1-M^2}} \tag{1}$$

$$m_{zstl} = m_{znestl} \frac{1}{\sqrt{1-M^2}} \tag{2}$$

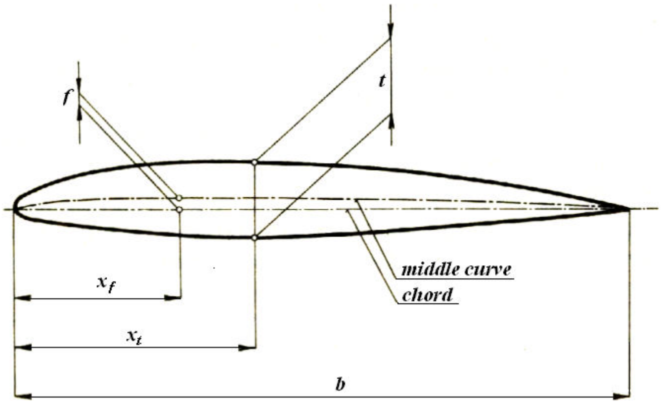

Fig. 1 Airfoil geometric characteristics

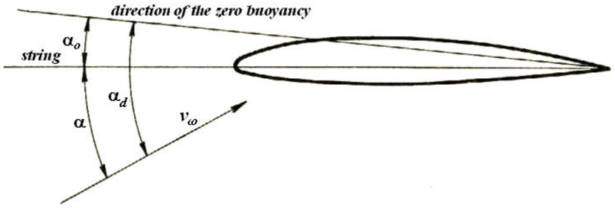

Fig. 2 Definition of the airfoil angle of attack

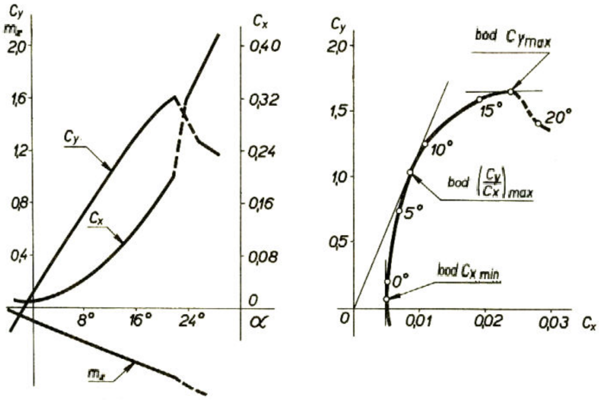

Fig. 3 Essential aerodynamic characteristics

These relations apply only in the subsonic regime. The aerodynamic centre of airfoils (the point whose moment does not change with changes in angle of attack at a constant speed) virtually does not move in the subsonic regime and approximates one quarter of the chord.

To make flying safe, it is necessary to know similar critical aerodynamic occurrences. The most notorious is the wing flow separation caused by the aircraft stall. Mach number is practically of no significance at low speeds. Similarly, the impact of Reynolds number is low with the same kind of airplane. The angle of attack and associated lift coefficient are the most significant values. In case the aircraft exceeds the allowed angle of attack (lift coefficient), stall occurs. Majority of airplanes are not fitted with the angle of attack indicators [2].

3. Effects of external load on the airplane structure

Airplanes can operate in several modes, such as take-off, climbing, flight, descent, landing and taxiing. Aircraft operate in one of the modes given before switching to another one.

Upon fulfilling tasks as designed by the aircraft purpose and mission, loads of different kinds are being generated. Throughout the aircraft lifespan, there is a combined load (made up of several types of load) acting on the aircraft structure in the long run or in the short run. The aircraft structure must be designed to bear such loads without having an adverse effect on the safe operation of the aircraft in question. In other words, no failures leading to incorrect function of the entire aircraft, its components and devices or threat of lives must occur.

There are two basic categories of load that airplanes must withstand throughout their lifespan, such as:

- *static loads,*
- *dynamic loads.*

Static loads do not change with time, they are constant. Most of loads acting on the aircraft structure are variable loads. A static load is considered merely the load acting on aircraft while standing on a runway, excluding the motions of the aircraft and air flow. This would make the strength calculation complex since all other instances of load would have to be calculated as dynamic loads. Therefore, static loads also include instances in which time changes can be ignored (always in a certain time interval). In case of static loads, it is necessary to identify their force action direction and area distribution [3].

Dynamic loads are those changing with time. Even the loads having been described as static in some time intervals, are described as dynamic in the same time intervals. It is not sufficient to have the force action direction, mean values or distribution available to identify dynamic loads. In addition, we must identify the frequency of load changes and load change size (amplitude).

Moreover, we can categorize:

- *concentrated loads,*
- *distributed loads.*

Concentrated loads are loads acting on the aircraft structure in one point only. In principle, they are loads generated by other suspended components acting on the structure. For instance, it may be the load generated by gravity of the engine unit. Concentrated load as a vector quantity is specified by its direction and center of gravity. In contrast, ***distributed loads*** act on the aircraft structure evenly, such as for instance load by aerodynamic forces or one's own gravity. In such instances, we must also know the distribution development and location in the aircraft coordinate system.

Airplanes can operate in several modes, and loads can further be categorized in the following manner:

- *loads acting on the airplane in flight,*
- *loads acting on the airplane during take-off, taxiing.*

Loads acting on the airplane in flight are represented by various types of motion. After rising into the air, the aircraft reaches the required altitude and continues flying horizontally, and eventually makes a descent and landing. Aircraft are capable of controlled changes in movement or directions in six motions. The changes include speeding up and down in straight flight, non-linear vertical flight, non-linear horizontal flight, and so on.

The air mass, in which the aircraft is flying, is considerably unstable which generates additional load on the aircraft by wind gusts. At high speeds, thermal loads must also be taken into consideration. Generally, loads acting on the airplane during flight can be categorized as follows:

- *loads in symmetric maneuvers* (with no acceleration),
- *loads in asymmetric maneuvers* (including acceleration).

Loads acting on the aircraft during take-off and taxiing is given by the size of reaction in the undercarriage legs of the landing gear. The reactions may take various values depending on the landing techniques and taxiing characteristics. Upon landing, the biggest loads act on aircraft on the ground. We may assume that the lift acting on the aircraft roughly equals its gravity. If we disregard the two counterbalancing forces, we may oversimplify that in cases of loads acting on aircraft on the ground, balance must be achieved between the ground reactions and inertia forces. They include:

- *reaction forces,*
- *manipulation forces,*
- *load by one's own gravity,*
- *inertia forces.*

Forces that receive much attention in designing and building landing gears are the reaction forces. They are the forces being generated in take-offs and landing, taxiing and standing on reinforced runways. They act on the landing gear units and those aircraft components to which they are attached (wings, fuselage). The additional reaction forces are generated in the joints located between individual aircraft components.

Manipulation forces are the forces of local effect, including:

- forces being generated during aircraft elevation for the purposes of maintenance and repair,
- forces being generated in the course of towing the aircraft (towing by the front undercarriage leg).

The strain itself is of low significance in aircraft structures compared to other types of load. However, the aircraft gravity value is the fundamental quantity affecting the flying performance and capabilities. The load of individual aircraft components generated by the gravity occurs in its mass which is located in the gravitational field of the Earth. The value of such gravity is given by the relation:

$$G = m.g \tag{3}$$

where G is the aircraft gravity (N), m is the weight of the aircraft (kg) and g is the acceleration of gravity of the Earth ($m.s^{-2}$).

It follows that a negligible change in the acceleration of gravity depends on mass only. The resulting gravity can be replaced by vectors positioned close to the centre of gravity of the structural unit in question. We will calculate the resultant force of the entire aircraft gravity from the sum of all aircraft weights and the resultant force will cross the aircraft material centre of gravity. The total weight depends on the payload weight, the empty structure weight does not change. The position of the aircraft centre of gravity varies with the payload distribution. The direction of the gravity action is given by the direction of the Earth's acceleration of gravity. It is manifested by the load acting in one or several points of the structure or by the continuous distribution load in longitudinal and transversal direction of the aircraft coordinate system. In addition to the value of gravity, weight distribution, centre of gravity position and the resulting tensile force action are of importance [4,7].

Load by inertia forces is generated in accelerated movement of objects. In accelerated motions (straight or rotational) initiated by the internal accelerating force (moment), the identical size of inertia (moment) is generated. Inertia counteracts the acceleration force (moment). Considering the accelerations performed during maneuvering, these loads cannot be ignored, in particular in large aircraft components (wings, fuselage, etc.). Both categories of force, i.e. tensile and inertia forces, are given by the aircraft weight or its component weight, therefore they will be referred to as weight forces. The resulting weight force is given by the vector sum of the respective object's own gravity and acceleration force being generated in accelerated motion [8].

While in operation, there are also loads generated by various gyroscopic moments and thermodynamic effects, which we have not analysed in the paper.

For the purposes of calculations, we will use the following L-159 aircraft parameters:

- engine unit: Allied Signal, F124, maximum thrust of engine 28kN,
- length: 12 730 mm,
- wingspan: 9 540 mm,
- height: 4 770 mm,
- weight of empty aircraft: 4 160 kg,
- maximum take-off weight: 8 000 kg,
- maximum cruise speed: 935 km/hour, max.
- flight ceiling: 18 200 m,
- flight ceiling: 48 m/s,
- operation range with additional fuel tanks: 2 530 km.

Armament of L-159 aircraft:

- AIM – 9 Sidewinder A-A,
- AGM – 65 Maverick A-G guided missiles,
- ZPL – 20 (20 mm) aircraft cannon,
- max. weight of ammunition 2 340 kg,
- cartridge: 20x102 mm,
- principle: multiple barrels,
- engine: internal,
- rate of fire: high 2650 min^{-1},
- low 750 min^{-1},
- weight 67 kg,
- dimensions: length 2000 mm,
- width 180 mm,
- height 200 mm.

Fig. 4 L-159 ALCA aircraft

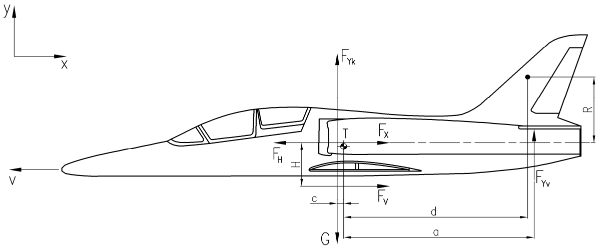

Fig. 5 Forces acting on the aircraft on the axis X-Y

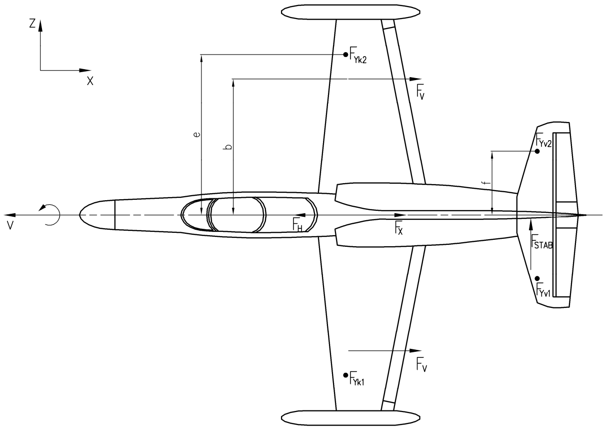

Fig. 6 Forces acting on the aircraft on the axis X-Z

Force balance equation:
$\sum F=0$
$\sum F_x=0$; $F_H - F_x - F_v = 0$
$\sum F_y=0$; $F_{Yk1} + F_{Yk2} - G + F_{Yv1} + F_{Yv2} = 0$
$\sum F_z=0$; $- F_{STAB} = 0$
Moment balance equation transmitted to the aircraft centre of gravity:
$\sum M = 0$
$\sum M_x=0$; $F_{Yk2}.e - F_{Yk1}.e - F_{STAB}.R + F_{Yv2}.f - F_{Yv1}.f = 0$
$\sum M_y=0$; $F_V.b - F_{STAB}.d = 0$
$\sum M_z=0$; $F_{Yk1}.c + F_{Yk2}.c - G.c - F_{yv1}.a - F_{yv2}.a - M_z = 0$

Next, it is necessary to calculate the aircraft minimum speed with the following input conditions available:
- flight without devices which increase the lift on wings (such as flaps, etc.),
- elevation 0 m – zero elevation of standard atmosphere,
- weight m = 7 500 kg, i.e. full fuel tanks, first pylon empty, the second pylon ZPL-20, the third pylon AIM–9 (weapon systems needed to accomplish combat missions).

$$v_{\min} = \sqrt{\frac{2F_G}{c_{y\max}.\rho.S}} \tag{4}$$

where $F_G = m.g$, m is the weight of the aircraft (7 500 kg), g is the acceleration of gravity (9,80665 $m.s^{-2}$), c_{ymax} is the lift coefficient, ρ is the air density (1,2255 $kg.m^{-3}$), S is the area on which the lift is acting (18,3595m^2).

$$v_{\min} = \sqrt{\frac{2.7500.9{,}80665}{0{,}670.1{,}2255.18{,}3595}} \tag{5}$$

$v_{min} = 9{,}8\ m.s^{-1} = 352{,}8\ km.h^{1}$.
Having simplified the input conditions, the weight of the aircraft will be 4160 kg minus the empty aircraft weight $v_{min}=73{,}6\ m.s^{-1} = 265\ km.h^{1}$. It is not necessary to consider the weapon systems as the aircraft does not carry any.
We will calculate the Reynolds number:

$$R_e = 68000.v.b_{rudder} \tag{6}$$

where v is the speed of flow [$m.s^{-1}$] a $b_{rudder} = b_a$ – mean aerodynamic depth of the rudder [m]. The resultant values are as follows: R_e=68000.98.1,6 and R_e=10 662 400.

The input conditions to calculate the aircraft stabilization are as follows:
- straight flight,

- we disregard F_x (various types of resistance, the so called parasite drag) that is several times lower than the forces acting in the course of firing,
- we disregard the inertia engine moment being transmitted to the engine arrangement in the aircraft structure.

The moment condition to keep the aircraft in a stable position after firing (the aircraft will avoid spiral descent) is as follows:

$$M_{STAB} \geq M_{vyst} \tag{7}$$

where: M_{STAB} is the stabilization moment and M_{vyst} is the moment generated by the fire of cannon.
The following simple equation is used to calculate the moment generated by the fire of cannon:

$$M_{vyst}=\Delta F_v.b \tag{8}$$

where: F_v is the force generated by fire [N] (16kN, at high rate of fire), b is the distance of the cannon axis from the aircraft axis [m].
The force F_y is found experimentally, the calculated values of the moments generated by the fire of cannon are as follows: M_{vyst}=16000.2,57 and M_{vyst}=41120Nm.
To calculate the stabilization moment, the following equation can be used:

$$M_{STAB}= \Delta F_{YSOP}.d= \Delta F_{STAB}.d \tag{9}$$

where: $F_{YSOP} = c_Y \frac{\rho v^2}{2} S$ and c_y is the lift coefficient.
It follows from the given values that if having a floating tail assembly, the deviation by **α = 9,27**° angle is a must at the moment of fire in order to keep the flying aircraft stabilized. The following condition must be met:

$$M_{STAB} \geq M_{vyst} \tag{10}$$

i. e. **44 739Nm>41 120Nm**

Currently, L-159 stability is guaranteed by the onboard computer together with a fire blocking device when firing the ZPL-20 airborne cannon. The blocking device is to restrict the use of the weapons system at low speeds and low altitudes.

There are some drawbacks associated with providing the flight stability in this manner. Yet, L-159 is a combat aircraft designed to perform combat missions under any circumstances. If restricting the use of the weapon system in combat, the lives of air crew and the success of the military operation may be put in danger.

Fysop	[N]	[°]	ΔFysop	Mstab [Nm]	Mstab (Δ)
Fysop	0	0	0	0	0
Fysop	181,9310048	0,08	181,93	790,85	790,85
Fysop	1650,374115	1,1	1468,44	7174,17	6383,32
Fysop	3170,797513	2,14	1520,42	13783,45	6609,28
Fysop	4483,299762	3,17	1312,50	19488,90	5705,44
Fysop	5704,836509	4,19	1221,53	24798,92	5310,02
Fysop	6861,397897	5,21	1156,56	29826,49	5027,57
Fysop	7965,978998	6,22	1104,58	34628,11	4801,61
Fysop	8914,619237	7,23	948,64	38751,84	4123,73
Fysop	9785,289046	8,25	870,66	42536,65	3784,80
Fysop	10292,09685	9,27	506,80	44739,74	2203,09

Table 1 Calculated values of F_{YSOP} and M_{STAB}

To provide for the combat effectiveness, it is necessary to eliminate any restrictions related to the use of the weapon system and to adopt such an option that will permit firing while not endangering the crew due to the loss of thrust or lift.

Following the calculations and available data, there are the following options:

- to vectorize the engine thrust and have a reserve in the respective moment of fire,
- to increase the engine thrust immediately – can be provided by interactivity of the onboard computer and regulation of the fuel system. Upon activating the weapon systems, the following changes will occur:
- low temperature at the engine input,
- high revolutions,
- „poor" fuel mixture.

There is a sudden enrichment of the fuel mixture and increase of the engine performance at the moment of fire. It is more advantageous to use weapon systems with lower recoil (for instance heavy machine gun 12,7 mm). Nevertheless, fire effectiveness of ZPL-20 aircraft cannon is remarkably higher, thus more suitable for performing combat missions.

4. Selecting proper material for exposed construction nodes

In addition to fuselage and wings, pylons and cannon barrels rank among the most exposed construction nodes of the L–159 aircraft. Informative calculation for the barrel is made in the Cosmos software. The proper material is the following:

The proposed material is steel 15 230, STN 41 5230
$E = 2{,}16.10^{-5}$ MPa (Young's modulus)
$R_e = 850$ MPa (yield point)
$R_m = 1000 – 1200$ MPa (ultimate strenght).

The loading force (pressure) is the maximum pressure acting inside the barrel p_{max}=349 MPa. The development of pressure after fire is very fast and of steep ascends; and for the purposes of calculation it is necessary to divide the barrel into two parts. The calculation can be made only for the part located closer to the loading chamber. Its length is of 48 mm giving the trajectory and time of the maximum pressure action [5].

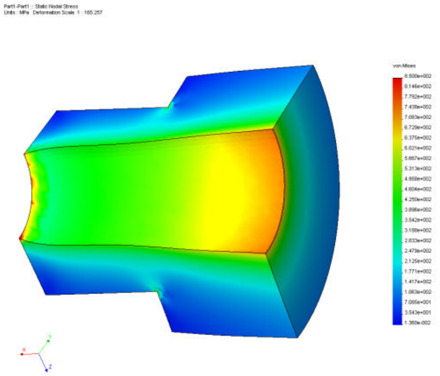

Fig. 8 Stress development in the barrel

Fig. 8 illustrates the simulated development of stress. Barrel parts marked in red exceed the defined yield point. The maximum stress reached the value of 832 MPA. Yet, the stress acts on the material only for a short time (approximately 0,2 s); no plastic deformation will occur and the material will get hardened to a certain depth of the surface layer.

Fig. 9 shows the development of deformations. The maximum deformation is of 0,02 mm. This deformation can be disregarded if considering thermodynamic effects and abrasions generated by fire. The following exposed nod is the pylon on which the cannon is mounted. Pylons serve not only to carry but also position the weapon. The calculation is to identify the development of stresses and deformations in the pylon pivots that connect the airplane container and cannon pylon.

The following boundary conditions are available to perform informative calculations:

- cannon weight is 68 kg,
- weapon was positioned, internal and external cannon pylons are secured in the position given,
- the extreme case is being considered to perform the calculation, i. e. the failure of the damping coil decreasing some of the forces generated by fire.

Proposed material: steel 15 230, STN 41 5230.

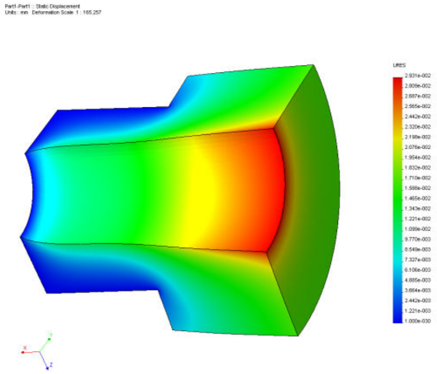

Fig. 9 Development of deformations inside the barrel

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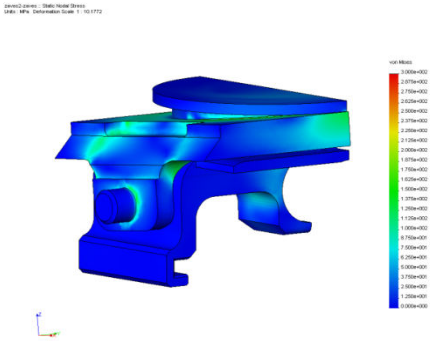

Fig. 10 Development of stress in the cannon pylon

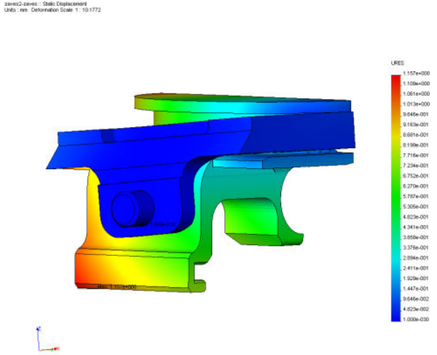

Fig. 11 Development of deformations in the cannon pylon

The previous calculations confirm the correctness of the proposed material, i.e. steel 15 230 both for the barrel of 20 mm ZPL-20 cannon and the cannon pylon in the air container [5,9,10].

5. Conclusion

The issue of high safety and dependability of aviation technology is extremely demanding and complex. The issue of high safety and dependability covers the process of designing any type of aircraft while taking into consideration the current requirements. In addition to fundamental requirements of design, they include the requirements related to the aircraft performance and flight parameters, maximum dependability, minimum weight, maximum toughness and minimum operational costs.

Calculation of the aircraft stability is one of the initial conditions to design the aircraft structure. To tackle the issue of stability, it is necessary to know all the load-related conditions of aircraft on which all the remaining aircraft characteristics depend (aircraft performance and consumption, aircraft weight, the design related to changes in the aircraft structure, etc.)

The findings obtained are absolutely necessary to guarantee safety and dependability and to succeed in combat operations.

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