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FINITE ELEMENT ANALYSIS OF THE SUSPENDED SATELLITE MISSILE WEIGHT EFFECT ON STRENGTH AND DEFORMABILITY OF THE MIG-29 AIRCRAFT STRUCTURE

Aleksander Olejnik1), Piotr Zalewski1), Robert Rogólski1),
Michał Jędrak1), Michał Szcześniak1)

1)Military University of Technology - Faculty of Mechatronics, Armament and Aerospace

Abstract

The paper presents selected aspect of the research project entitled: *Airborne-and-missile system of delivering satellite payloads to low Earth orbit - feasibility study*. The aim of the project is to conduct series of aerodynamic, aeroelastic and strength simulation of Polish aging combat aircraft (Mig-29 and Su-22) to assess the possibility of using one of them as an airborne platform for carrying a missile with a detachable satellite payload. This work presents airframe load and strength analysis of the airframe of MiG-29 for assumed operational variants with carrying missile under-fuselage suspension. The numerical simulations were conducted on the structural discrete model of the aircraft prepared for finite element analysis in MSC Patran. Model development involved such aspects as precise discretization of geometric model, declaration of material constants, identification of structural properties, introduction suitable merging connections for included airframe assemblies, final model weight and stiffness validation. The model was analysed in MSC Nastran and LS Dyna software. For the purposes of the calculations, the IMPLICIT analysis type was selected in the field of linear statics. The flight loads introduced into the model were calculated for specific points of the flight envelope - the highest values of load factor were taken into consideration (n=9). The counterpart aerodynamic force distribution in a form of a set of equivalent lumped forces was calculated. Then the aerodynamic forces were added using the forces applied to the wing at the model nodes along the span. A gravitational load with an appropriate overload factor was simulated also. Missile masses were taken into account by concentrated forces applied on the attachment of the suspension frames. Calculations were made for missiles of several weight values between 800 and 1500 kg. Parametric dependencies were investigated of the impact of missile weight and size on the stress distribution over the whole structure. The areas of stress cumulations and were identified. Apart of that the modes of static structural deformation were simulated which allowed to assess maximum wing tip displacements during the flight in ultimate conditions.

Keywords: FEM modelling, flight loads, airframe structure, static analysis

1. Introduction into the problem

The concept of Airborne-and-missile system of delivering satellite payloads to low Earth orbit (LEO) is an alternative solution with respect to the traditional way of launching a small satellite into space - by launching a transport missile directly from the ground. The proposed method takes into account the launching of a flying object carrying out a payload launch mission in the course of three flight stages:
- the flight of an aircraft with a carrying missile attached to the airframe has a maximum altitude,
- The flight of a detached missile to orbital ceiling,
- separating the satellite payload from the missile and placing it on an orbital trajectory.

The solution, due to limitations of the missile size, is rather dedicated to miniature satellite payloads (microsatellites), i.e., weighing several kilograms or even several dozen kilograms. Analyses of operational and technical capabilities for this type of missions have been described in publications [1], [2], [3].

While considering the possibility of launching such a program in Poland, we may take into account two types of combat aircraft which could potentially be used for aerospace satellite launching missions. The Su-22M4 and MiG-29A aircraft still maintained at Polish Air Force tactical aviation bases are likely to be withdrawn from service soon, due to their obsolescence and lack of operational usefulness. However, after being withdrawn from service, some of those aircraft could serve as potential "transporters" of missiles carrying miniature space payloads. Due to its younger age, more robust design and more modern technological solutions, the MiG-29 seems to be a better candidate for potential use.

This paper presents an analysis of the case of this particular aircraft in the aspect of evaluation of external loads as well as strain and deformation of the support structure as a result of in-flight interactions with a suspended satellite missile. Taking into account the distributions of aerodynamic and mass forces as well as the weight of the missile suspended at the fuselage nodes, finite element model (FEM) analyses were carried out. The determined stress and strain distributions of the virtual model structure allow to assess the airframe usability in terms of safety and reliability of the structure. The discrete model of the airframe has been developed using MSC.Software (Patran preprocessor) and LS Dyna (PrePost). The software analyses covered the process of model building - taking into account the desired material properties and the required elemental relations. Then, the model support conditions and loads equivalent to the real in-flight loads were defined. Both aerodynamic and mass loads were approximated by a substitute system of concentrated forces applied in specific model nodes. The mass load coming from the suspended missile was represented by two concentrated forces applied to technologically reinforced mounting points. Analyses were performed for several mass variants assuming the range of possible missile weight values from 800 to 1250 kg. Methodology of simulation analysis of aircraft structures based on discrete FEM models has been developed for at least four decades and is successfully used both in scientific and research tasks as well as engineering problems formulated for the needs of the aerospace industry. Theoretical assumptions and calculational rules for airframe components treated like thin-walled structures are completely reported in bibliographic positions like [4], [5], [6] and many other of course. The applied computational techniques based on FEM and achieved results have been presented in many publications; among them we can cite ones of the newest: [7], [8], [9]

2. Discrete structural model of the MiG-29 aircraft for FEM

The technique of structure modeling using software tools for FEM analysis is a standard procedure used in the course of identification of strength and vibration properties of aircraft. The process of creating a virtual model of the structure for calculations and simulation of possible aero stress phenomena is a time-consuming activity, requiring prior preparation and arrangement of geometric and structural data of the object. Additionally, the reliability and credibility of all measurements and expert opinions related to the determination of the data is required, which in turn strongly depends on the qualifications and knowledge of engineers preparing the virtual model. For the purpose of developing the model correctly representing the stiffness and mass properties of the real structure, it is necessary to collect the following sets of data:

- airframe geometric data – record of the model of structural geometry in CAD environment together with a set of detail and component drawings;
- structural and technological data - arrangement of details within particular load-bearing units (wings, fuselage, empennage), types of materials used and their processing, ways of connecting elements and structural units, kinematic connections of mechanized fragments of the structure;
- mass data - location and size of the on-board aggregates (masses, moments of inertia), equipment and cargoes foreseen in the contemplated operational variants (so-called non-structural mass).

2.1 Geometric model of an aircraft with an underslung carrying missile

For the purpose of structural modelling, a model of the MiG-29 aircraft geometry, developed at the Institute of Aviation Technology WML WAT, was used. The model geometry was developed on the basis of real airplane measurements - with the use of reverse engineering (RE) tools and software algorithms. The methods used in this work are known from publications such as [10] or [11]. The base model has been complemented with a parametric model of a transport missile defined by means of the GRIP internal programming language code, which enables parametric modelling of object geometry in the space of the Siemens NX PLM environment. For the strength analysis purposes, the missile model was not particularly useful, as the simulation of the suspension was performed by setting the mass forces applied at the anchor points. However, visualization in CAD environment of the complex model system (airplane + missile) shows the proportions of the components (Fig. 1). The model will also be useful in the context of preparing the spatial mesh of the flow grid around the object for later CFD analysis.

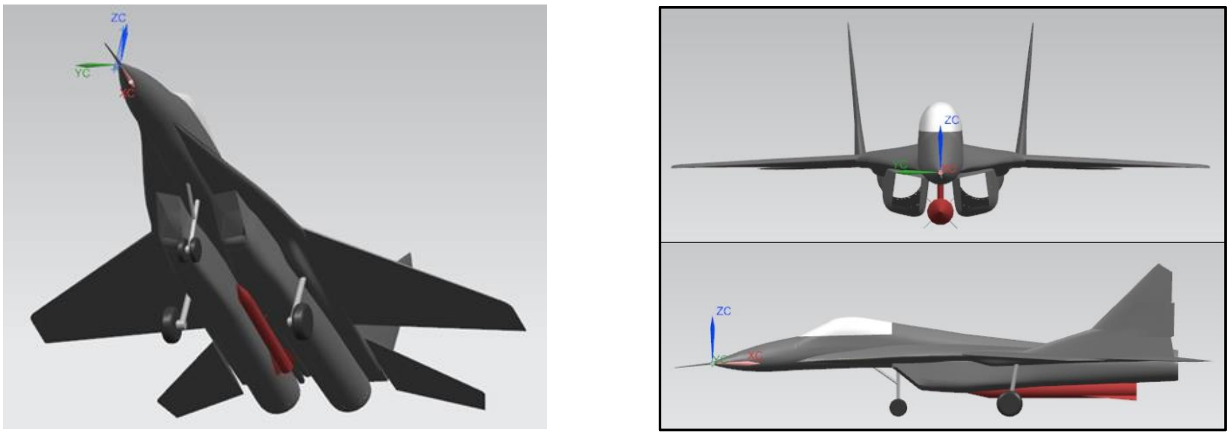


Fig. 1: CAD model of MiG-29 aircraft with a hypothetical carrying missile suspended under the fuselage.

Modeling of the internal geometry was completed by supplementing model of “washed out” surface with additional surface elements located in the cross-sectional planes of the real structural elements of the airframe. To define locations of these elements the drawings and descriptions available in some high-fidelity technical monographies as [12], [13] were used. As the technological-and-operational documentation of the airframe was available [14] many data items was identified from it. The geometry model ready to discretize the structure including the covering surface and the surfaces representing the internal elements (frames, ribs, walls, girders and others) is shown in Fig. 2.

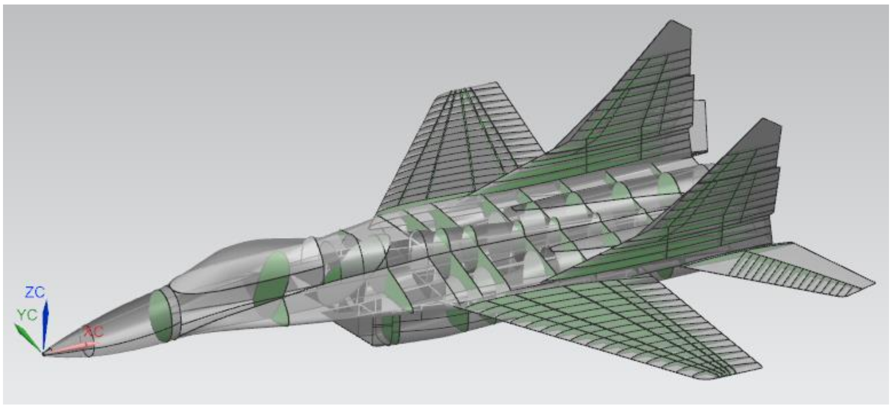


Figure 2: Comprehensive model of aircraft surface geometry including internal structural elements.

2.2 Discrete airframe model for the finite element method (FEM)

The discrete structure generated in the MSC Patran preprocessor on the basis of the model geometry is built of basic shell elements (triangular or quadrilateral) and complementary one-dimensional elements (rod or beam) (Fig. 3). The mobility of rudder and aileron joints was ensured by using RBE type rigid elements and CELAS spring elements. Material properties of the elements were introduced according to the real use of materials in particular areas of the structure. Material constants such as Young's modulus, Kirchoff's modulus, Poisson's number (E, *G*, ρ) were introduced on the basis of literature data on specific materials or their equivalents. Fig. 4 shows an example of material distribution on the background of the wing model structure.

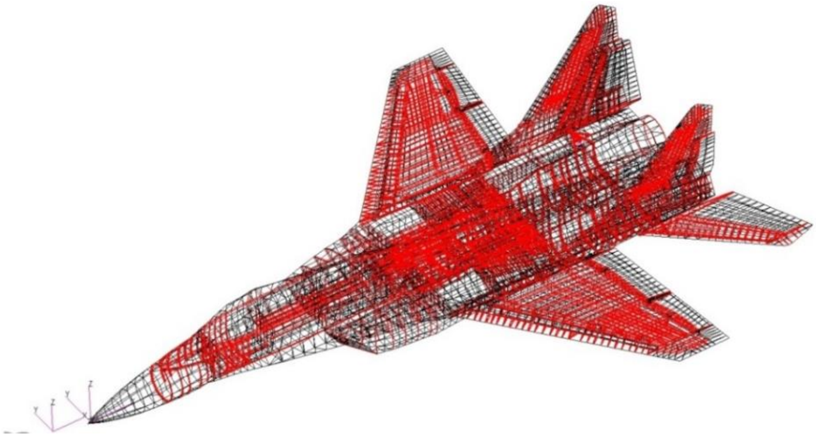


Fig. 3. Element model of MiG-29 aircraft for FEM strength analysis (60 000 DOF).

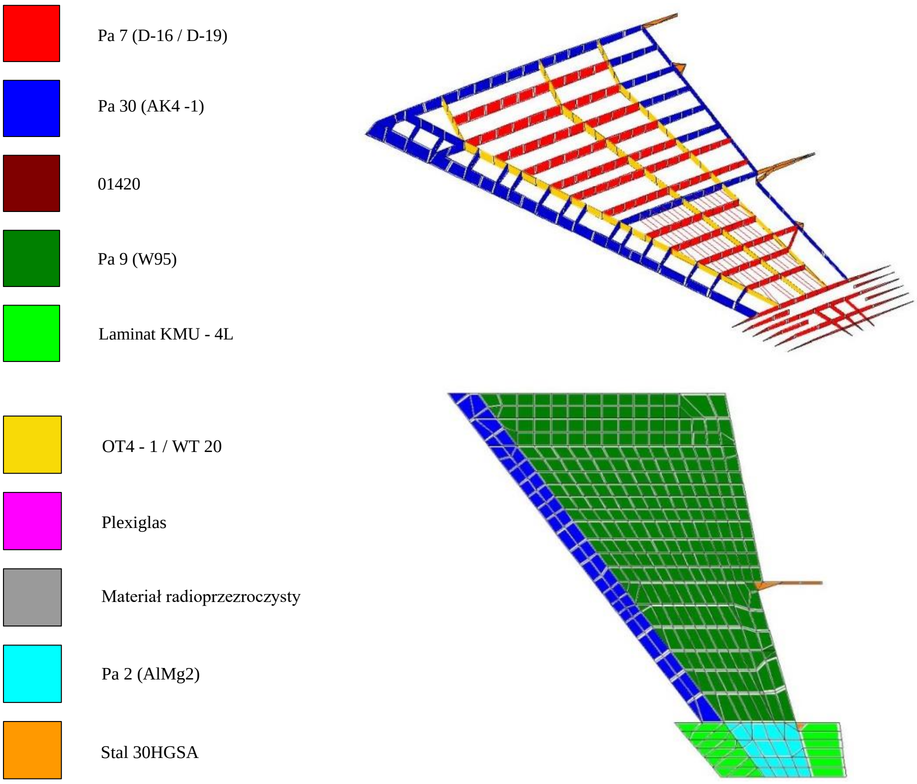


Fig. 4. Distribution of structural materials on the example of the wing structure - the major part of duralumin alloys Pa-7, Pa-9 and Pa-30.

The element model has both stiffness and mass properties, as both moduli and densities are defined for the materials highlighted. The following three types of static loads will be considered in the strength analysis: 1) those from aerodynamic forces, 2) the weight of the aircraft structural mass, and 3) the weight of the satellite payload missile suspended from the sub-fuselage nodes. The mass forces coming from the airframe structure as well as from the installed systems and elements will be taken into account as a system of equivalent concentrated forces applied to particular nodes of the model structure. Thus, the static model is characterized by the mass of the structure and the stiffnesses of the individual support assemblies.

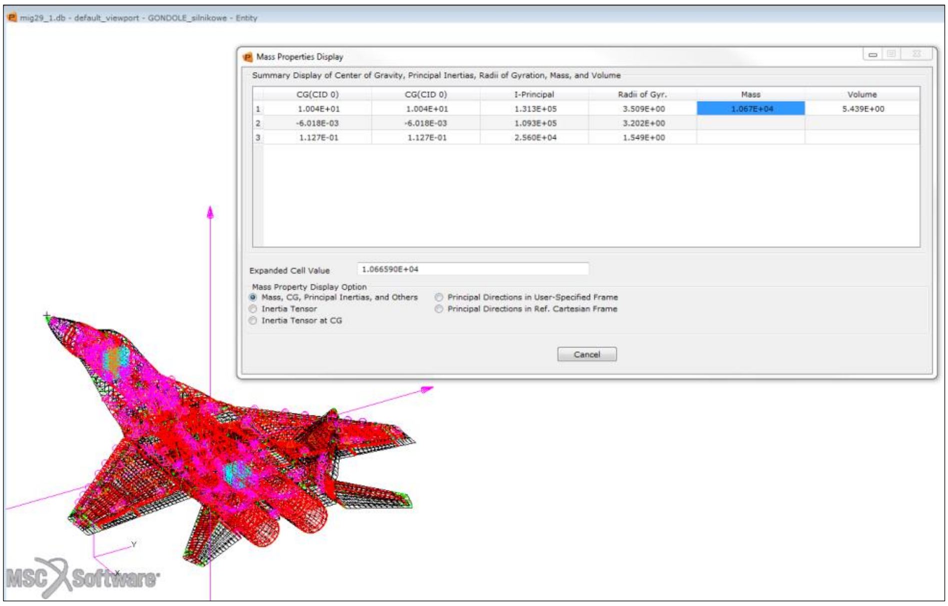
2.3 Method of validation for some structural properties of the model

Before running the target computations, the model should be subjected to validation checks to assess the suitability in terms of obtaining reliable results. Stiffness assessment of structural components is rather problematic. No experimental stiffness or strength tests of the airframe have been carried out, so there is no possibility to refer to the deformation quantities which would result from real loads. However, the values of operational masses are known (or can be estimated), so it was possible to validate at least selected mass parameters of the model.

The basic model of MiG-29 airplane has a model mass resulting from taking into account only the structural elements. In order to validate it, the basic model was extended by adding to it elements of the so-called non-structural mass. This group includes the mass of engines, power systems, electrical installation, electronic devices and fixed on-board equipment.

According to official data the empty weight of MiG-29 plane is 10900 kg. While developing the discrete model in Patran preprocessor, an attempt was made to define structural materials and properties of structural assemblies in such a way that the total model mass for the variant - empty mass would be close to that value. The mass of the supporting structure of the MiG-29 aircraft model was estimated by the preprocessor at 4990 kg, which means a mass shortfall of 4561 kg. On the basis of literature data, repair documentation and own measurements made on the plane overhauled at Polish Military Aviation Plants No. 2 (WZL 2), a list of masses of fixed airframe equipment was prepared. The masses of engines, fuel and power units and radio-electronic devices were identified. Geometric centers of these elements have been estimated - these points have been accepted as approximate mass centers.

The total weight of installations, aggregates and on-board equipment was estimated at 4700 kg, including: airframe and engine aggregates: 3500 kg, weapon system aggregates: 400 kg, electrical system and equipment accessories: 350 kg and radio-electronic equipment: 450 kg. The total model mass including structural mass and concentrated non-structural masses was 10700 kg; the center of mass was located in 25.8% of the SCA (Fig. 5). Thus, the model mass is understated by 1.8% in relation to the real mass, while the location of the center of mass is almost identical to the real location, which according to the technical document [15] is 25.6% MAC (mean aerodynamic chord).



Summary Display of Center of Gravity, Principal Inertias, Radii of Gyration, Mass, and Volume

	CG(CID 0)	CG(CID 0)	I-Principal	Radii of Gyr.	Mass	Volume
1	1.004E+01	1.004E+01	1.313E+05	3.509E+00	1.067E+04	5.439E+00
2	-6.018E-03	-6.018E-03	1.093E+05	3.202E+00		
3	1.127E-01	1.127E-01	2.560E+04	1.549E+00		

Expanded Cell Value 1.066590E+04

Mass Property Display Option
● Mass, CG, Principal Inertias, and Others
○ Inertia Tensor
○ Inertia Tensor at CG
○ Principal Directions in User-Specified Frame
○ Principal Directions in Ref. Cartesian Frame

Fig. 5. Total weight of MiG-29 airplane (model structure + non-structural weights) determined in Patran preprocessor; the value of 10700 kg was obtained and the center of gravity in 25.8% of MAC (axes of inertia).

3. Flight loads determination

For the elasticity and strength analysis of the airframe, it is necessary to know the loads acting on the airframe in flight. Precise determination of loads (magnitude, intensity, direction, distribution) is possible only for the specific mass-geometric case and in strictly specified operating conditions. Analysis of loads and strength is an indispensable stage of design, but in the perspective of later operational needs related to the complex overhaul, retrofitting or modernization, it is necessary to carry out recalculation in order to examine the impact of the intended change on the structure.

The values of operational loads should be within a certain area, the so-called permissible loads. The limits of this area are permissible to achieve, but not exceedable from the point of view of proper use. As a rule they are graphically represented as *n*-*V*, where *n* is the overload factor and *V* is the speed. The range of permissible operating loads is represented by a diagram called the flight envelope, whereby the flight envelope for maneuvering loads, the flight envelope for turbulent atmospheres (gusts) and the flight envelope for the flight envelope with flaps deployed are determined. Values of the characteristic points for these diagrams are determined according to the formulas specified in the aircraft construction regulations. The form of envelope for MiG-29 aircraft, determined in accordance with MIL-A-8861B (AS) [16] is shown on Fig. 6.

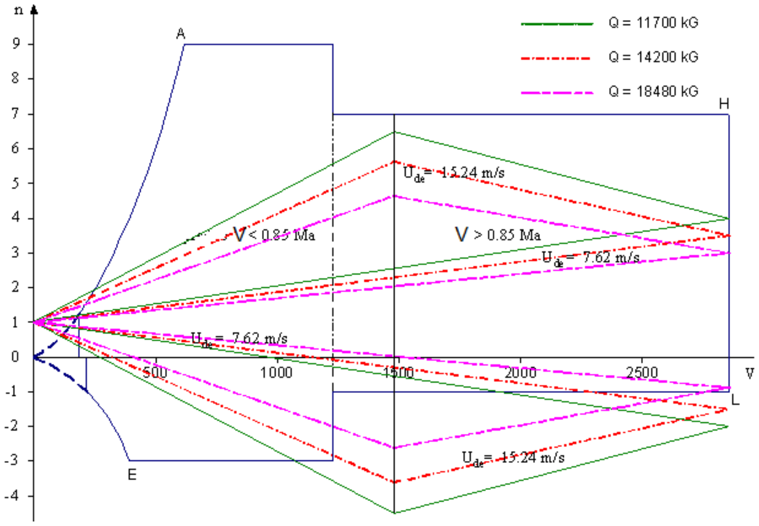


Figure 6: MIL-A-8861B permissible load envelope for the three weight variants of the aircraft.

Apart from the determination of the structure overload level expressing *n* times its weight in a specific operational variant, it is necessary to determine the load distributions in the areas of occurrence of particular structural units. All structural components of the airframe are subjected to in-flight loads as shown in Fig. 7. Obviously, the most heavily loaded and stressed component is the wing, therefore most attention is paid to this part of the airframe during the calculations. Apart from general requirements imposed on the aeronautical structures, additional requirements are imposed on the wing with regard to its correct torsional and flexural stiffness. This is to eliminate a number of unfavorable phenomena accompanying high-speed flights and large angles of attack, such as reduced aileron effectiveness, torsional divergence, flatter vibrations.

The following loads act on the wing during flight and when the aircraft is landing:

- aerodynamic forces;
- mass forces determined by the structure's own mass;
- mass forces coming from the aggregates and loads placed inside the airframe (fuel, engines, aggregates and system equipment);
- ground reactions (during taxiing, take-off and landing);
- the thrust of the power unit (especially when the engines are installed in the wing).

The aerodynamic and mass loads on the wing are defined by force intensity distributions denoted q_a and q_m, respectively. The mass loads coming from the node-suspended elements (under-wing and under-fuselage), system units, landing gear elements and engines can be approximated by the concentrated forces applied at the location points of the attachment nodes. The methodology for determining flight loads has been described in many academic and scientific publications, where the worth of citing are [17], [18], [19].

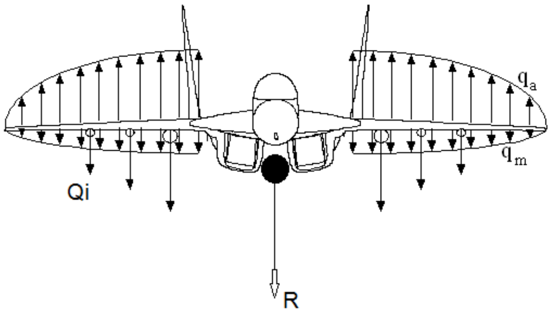


Fig. 7. Simplified flight load distribution – in general with lumped forces from underwing stores.

Determination of wing loads is identical with determination of its size, direction of action, and force distribution along its characteristic direction (span or chord). The loads depend on the shape and construction of the wing and the flight conditions. The starting point for determining the basic loads is the design overload coefficient n_0, which is the product of the operational overload (specified in regulations) n_e and the safety coefficient f. The coefficient n_0 is related to the lifting force P_z by the relation

$$P_z = Q \cdot n_0 \tag{1}$$

where Q is the aircraft weight in given flight conditions. For the purpose of analysis of the MiG-29 aircraft, the computational loads have been determined in a simplified way, assuming a discrete distribution of forces generated on partial elements (strips) of the aerodynamic surface. In MiG-29 aircraft, the fuselage also contributes to the aerodynamic force generation. However, a more restrictive variant of calculations has been adopted here, consisting in taking over almost the entire aerodynamic load by separated wing surfaces (according to distribution on Fig. 7). In simplification, the front flaps have been treated as a fixed integral part of the wing. To determine the discrete distribution of forces loading the wing, the following calculation formulas were applied

The total force acting on the surface of one wing:

$$P_w = 0{,}5 \cdot P_z \cdot \frac{S_w}{S_{ref}} \tag{2}$$

The total force acting on the wing surface without deflecting elements (tailplanes and ailerons):

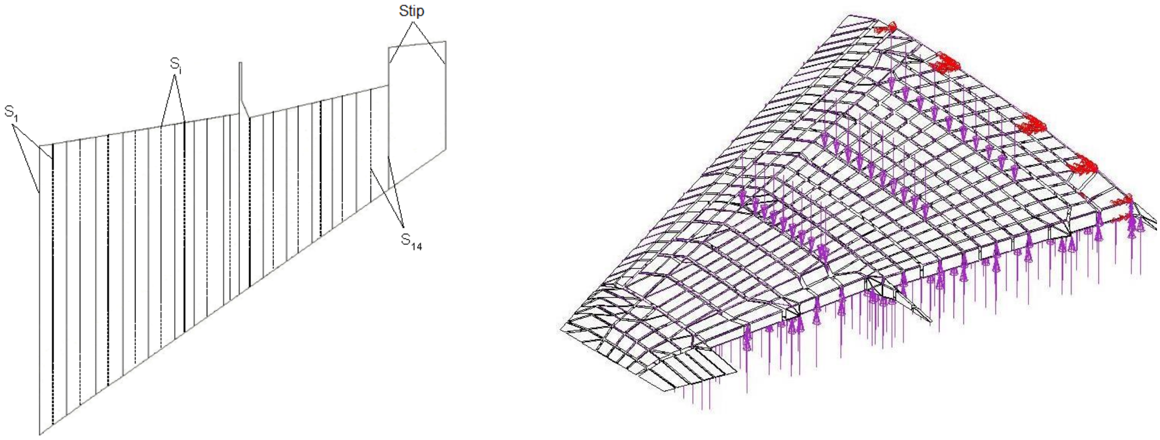
$$P_{ws} = P_w \cdot \frac{S_w - S_{fl} - S_{ail}}{S_w} \tag{3}$$

The symbols used in the above formulae refer to the following geometric quantities: S_{ref} - total bearing area, S_w - wing area (including swinging elements), S_{fl} - flap area, S_{ail} - aileron area.

For numerical calculations the load was distributed on nodes located in the rib planes. The design forces had to be distributed in such a way as to make their distribution as adequate as possible to the actual distribution resulting from the continuous distributions of the aerodynamic q_a and q_m mass intensities and the concentrated mass forces. For this purpose the wing was divided into 14 parallel surface strips. A partial force was determined for each aerodynamic strip, which was then applied to the model in the form of elementary forces applied to the structural nodes of each rib. Figure 8.a) shows the division of the wing into strips. Each elementary aerodynamic surface is denoted as S_i , where the subscript "i" denotes the number of the rib to which the given chord is associated. The adopted geometric division of the wing surfaces made it possible to calculate the resultant forces acting on particular surfaces S_i according to the formula

$$P_i = P_{ws} \cdot \frac{S_i}{S_w - S_{fl} - S_{ail} - S_{tip}} \tag{4}$$

It was assumed that the wingtip surface located beyond the plane of the aileron outer rib (S_{tip}=0,67 m^2) is not loaded. The application of model nodal forces finally determined as a result of distribution of P_i forces ($P1$ - $P14$) on the rib nodes is demonstrated in Fig. 8.b).



a) b)

Fig. 8. a) Division of the wing surface into design chord segments, b) simulation of the wing model loading by concentrated forces applied to the nodes in the rib planes.

For the model of the whole airplane to be statically analyzed it is necessary to define the complete system of loads acting on the airframe, balanced both in respect to the values of forces and the balance of moments with respect to the central axes of inertia. The balanced system of forces was obtained by adding the balancing load on the horizontal tailplane. Effects on the fuselage and vertical tailplane are considered as uniformly distributed mass forces, aerodynamic forces are omitted. In the final balance of equivalent loads introduced to the model, a simplified system of concentrated forces was taken into account. The simulation of stabilizer balancing forces is shown in Fig. 9.

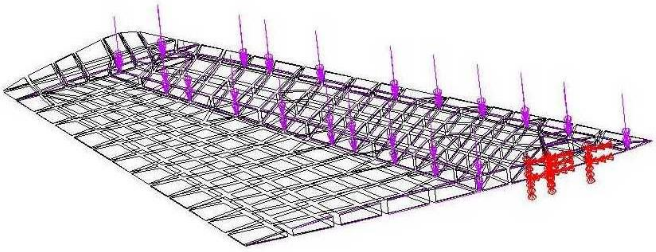


Fig. 9. Balancing load on the horizontal control arm in the form of a system of concentrated nodal forces.

4. Load case analysis and simulation results

For the overall model of the finite elements, the described load system and model boundary conditions were defined to allow analysis of the statically determinable case. Conditions corresponding to the free state in flight (unbounded object) are not acceptable for the Static Solution solver, requiring the introduction of immobilization with respect to all six degrees of freedom of the model body. Therefore somewhat artificial boundary conditions were set which correspond to apparent support of the model but do not introduce excessive stiffness. It was assumed that displacements of the model structure will be determined with respect to the internal chord of the wing located in the wing-fuselage plane. In each of the plains, two nodes were selected in the wing-fuselage connection points, which received translational degrees of freedom (Fig. 10). Finally, the model was immobilized by preventing the wing attachment nodes from moving in all three axial directions. As a result, the deformations of the model structure will be determined with respect to the stationary plane of the wing inner chords.

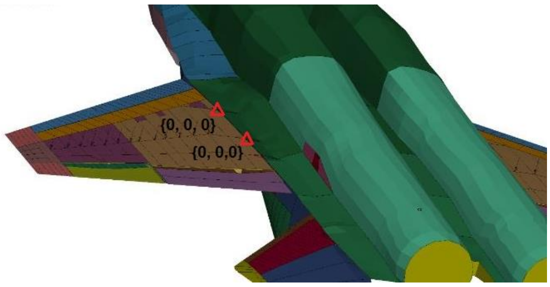
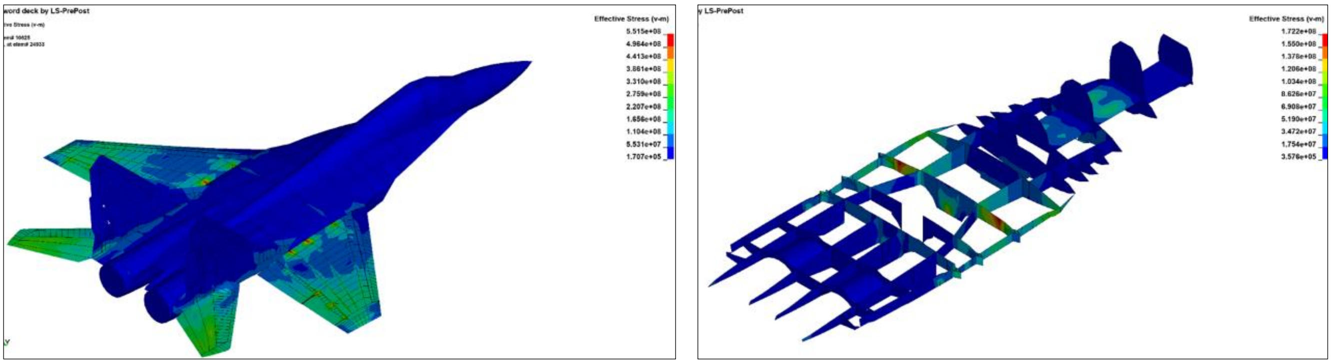


Figure 10: Designation of boundary conditions imposed on the discrete model before analysis in LS Dyna: {ux=0, *uy=0*, $_{uz=0}$}

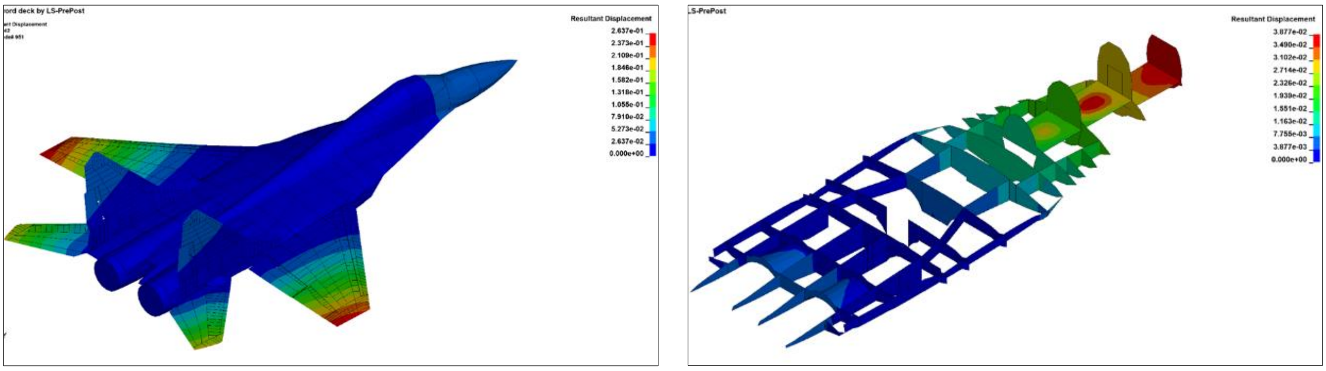
Additionally, by the LS DYNA system a gravity load was added by using LOAD_GRAVITY_PART_SET card. The maximum load factor $n_{max=9}$ was assumed. The load from a suspended missile with a parametrically variable mass in the range of 800 to 1300 kg was modelled by means of two identical concentrated forces acting vertically downwards, applied at the sub-body points of the attachment nodes of the suspended elements. Figs. 11 and 12 show example distributions of displacements and static stresses after numerical analysis of the model with given loads and boundary conditions. Series of analyses were carried out considering distribution of airframe loads corresponding to 1100 km/h velocity developed in conditions of aircraft acceleration in horizontal flight at high altitude (about 9000 m) before entering to the phase of maximum dynamic ceiling. A series of six calculation cases has been carried out for the aircraft mass of 14500 kg (aircraft + pilot + 70% of fuel quantity in integral tanks + suspended missile with satellite payload). Missile mass *mr* was considered as a parameter varying in the above-mentioned range of values

<800, 1300> kg, with a calculation step Δm_r=100 kg.



a) b)

Fig. 11. Distributions of maximum reduced stresses after analysis with LS Dyna program (*mr=800* kg): (a) imaging of stresses on the covering structure, (b) imaging of stresses in the internal structure.



a) b)

Fig. 12. Displacement distributions of the model structure after LS Dyna analysis (*mr=800* kg): a) imaging of displacements of the covering structure, b) imaging of displacements of the internal structure.

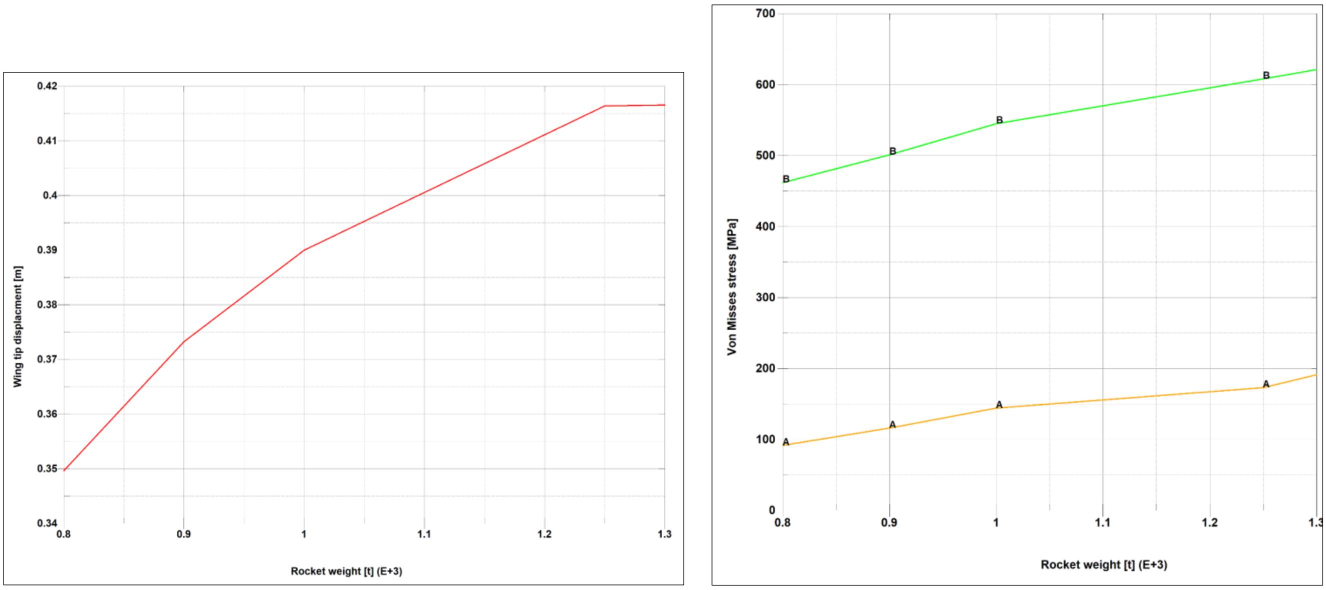


Fig.13. Function curves of maximal reduced stresses versus weight of the underslung satellite missile: (A) for under-fuselage hardpoints, (B) for wing-fuselage attachement.

5. Conclusions

As a result of a series of parametric model calculations, the distribution of displacements and static stresses of the MiG-29 structure has been determined for the considered mass variants of the satellite missile. The maximum displacements of the airframe have been identified (as expected) at the wing tips, while the zones of maximum stress levels occur at the nodes of wing-fuselage joints. The stresses in the suspension points of the booster missile were also analyzed. The highest values of displacements and stresses were obviously achieved after analysis of the variant with the maximum mass of the missile (*mr=1300* kg). The tip displacements were $_{utip=}$ 419 mm. For this kind of structure, the tip displacement value should rather not exceed 10% of the wing length. The span of a single MiG-29 wing is about 5.7 m, so a safe value slightly exceeding 7% was achieved.

In the case of stress distribution for the most loaded case, the value of the maximum reduced stress is 621 MPa and, according to the theory, it occurs at the nodes of fixing the spars to the hull. This value is less than the yield strength of the structural material (titanium alloy WT-20), whose ad hoc tensile strength is certainly not less than 850 MPa. So, also in this case, a value safely distant from the permissible one was reached. Stresses in suspension points adjacent to reinforced hull frames reach the maximum value of 190 MPa. These frames are made of PA7 aluminum alloy, for which immediate strength is about 400 MPa, so in this case also safe value is reached. The curves of the maximum wing displacements and the maximum stresses in the indicated points of their accumulation as a function of the suspended missile mass are shown in Fig. 13.

In the light of the results obtained, it can be concluded that in terms of safety of the structure's work, the MiG-29 aircraft can be considered as a potential carrying platform for the mission of launching a satellite payload missile.

Acknowledgment

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Copyright Statement

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