Finite Element Modeling of the Arresting Gear and Simulation of the Aircraft Deck Landing Dynamics

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Summary:

Deck arresting gear is a special aero-carrier unit that is destined to provide an efficient arrestment of the deck jet-fighters of masses 10-25 tons with high landing velocities between 180 and 240 km/h. Main elements of the modern arresting gear are a cable and a hydraulic system. During deck landing the jet-fighter grasps the cable with a hook and draws it. The cable is threaded between a system of blocks, that are forming a block-and-tackle mechanism, designated to transfer the jet-fighter pull to the hydraulic braking machine. In the latter the kinetic energy of the fighter is transferred to the heat and then dissipated.

Figure 1. Arresting gear cable drawing

In the current work a full-scale LS-DYNA model of the deck arresting gear is created. The model contains all basic elements of the real prototype and is used to analyze the dynamic behavior of the arresting gear with different arrestment conditions. Due to the feedback control system, several characteristics of the arresting gear elements vary with some of run-time changing parameters. Standard capabilities of LS-DYNA do not enable performing simulation of such a complex system and by that reason a Delphi code is developed. The code allows managing of LS-DYNA solution and automatically makes multiple restarts during the simulation to change the definition of stiffness and damping curves, describing the arresting gear parts. The developed model is used to obtain parameters of the arresting process – fighter displacement, velocity, acceleration vs. time, as well as pressure in the hydraulic system and tensile force in the cable.

Keywords:

Arresting gear, jet-fighter, cable, block-and-tackle, control system, hydraulics

1   Introduction

Arresting gear is a unit installed at a deck of the carrier to provide an efficient arrestment of jet-fighters with high landing speed between 180 and 240 km/h. Arresting gear is a hydraulic plunger brake connected with a cable stretched across the deck. Jet-fighters deck landing (Figure 2) is one of the most complex and critical stages of the flight from the safety point of view and though it requires both skilled actions of the pilot and failure-free operation of the arresting gear system. One of the factors that guarantees the safety of the deck landing is the dynamic strength of the arresting gear structural elements and optimal "fine tuning" of the system for the arrestment of the jet-fighter with specific mass and specific landing velocity. Statement and solution of mechanical problems for such a complex system is extraordinary challenging, as the phenomena to be described are high-speed and non-linear and though require application of the modern CAE technologies.

Figure 2. Arrestment

In the current paper the procedure of development, validation and utilization of numerical LS-DYNA model of the arresting gear is described. The developed model is applied for simulation and analysis of the landings with different parameters.

2   Operational principles of the arresting gear

Arresting gears operational scheme was constantly being under development and modification since the beginning of the 20th century. Till 1927 gravity-based arresting gears were in use: kinetic energy of the arrested fighters was converted into the work done to translate sandbags laying on the deck. Afterwards the friction-based arresting devices appeared. Starting from 1937 most carriers were equipped with hydraulic arresting gears – prototypes of the modern devices.

The modern arresting gear (Figure 3) represents a hydraulic braking machine, connected through the block-and-tackle and the system of blocks and dampers to a take-up cable that is stretched across the deck. During the deck landing the jet-fighter grasps the take-up cable (3) with a hook. The take-up cable is coupled by connecting muffles (2) with the braking cable (7). Thanks to the division of the arresting gear cable into two parts - take-up cable and braking - it is possible to interchange periodically the take-up cable, because its external plies undergo abrasion and rupture due to dynamic contact interaction with the fighter hook. The braking cable is threaded between a system of blocks, that are forming a 18x block-and-tackle. Rotational axes of blocks are installed at a movable (10) and a fixed (12) carriages. During the landing the braking cable is being drawn and the movable carriage runs towards the fixed one. The movable carriage is fixed at the plunger (9) of the hydraulic cylinder

(8), and the former is forcing the oil through the control valve (14) into the accumulator (5). Accumulator is consisting of two balloons separated by the piston (4) and during the landing the pressure in the air balloon (6) is increasing. Fighter mass selector arm (15) is located at the control vale. This arm allows to set the initial closure of the valve, depending on the expected value of the fighter mass to be landed. The movable carriage is connected through a feedback cable (17), driving chain (13), cam and arms (18) with the control valve so that the latter is being closed during the landing, reducing the cross section of the hydraulic system and thus increasing its resistance. This system guarantees an equal braking distance for a wide range of aircraft masses.
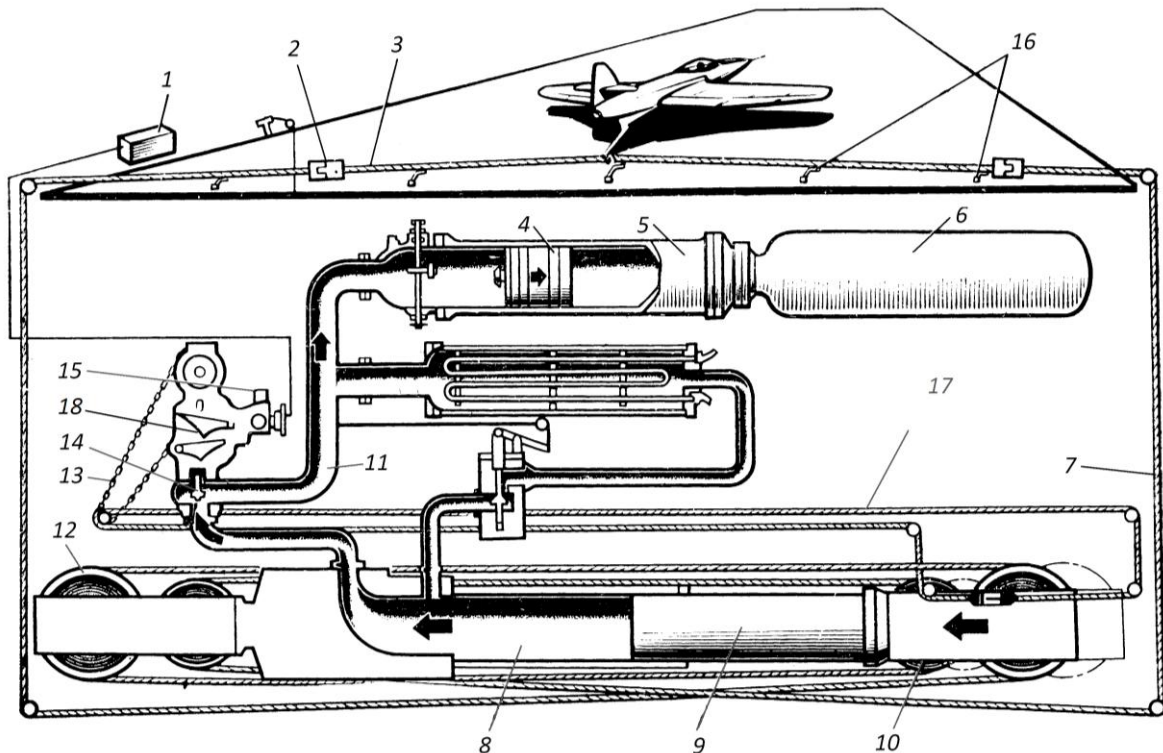
Figure 3. Arresting gear scheme
1 – control panel; 2 – connecting muffle; 3 – take-up cable; 4 – accumulator piston; 5 – accumulator;
6 – air balloon; 7 – braking cable; 8 – hydraulic cylinder; 9 – plunger; 10 – movable carriage;
11 – pipeline; 12 – fixed carriage; 13 – driving chain; 14 – control valve;15 – fighter mass selector arm;
16 – cable raiser; 17 – feedback cable system; 18 – control valve arms.

3   Mathematical model

The design model and the structured block diagram of the arresting gear are shown at Figure 4 and Figure 5 correspondingly. The problem of arresting gear dynamics is a high-speed and non-linear and, so general equations of rigid body dynamics together with equations of the wave motions in cable should be used in the analysis. Contact interaction between blocks and cable is to be considered as well. Hereby, to analyze such a complex model it is necessary to consider a system of non-linear PDE including but not limited to the following equations:

a) waves propagation in the cable:

$$\frac{\partial \dot{\underline{r}}}{\partial S} = \frac{\partial}{\partial t}\left((1+\varepsilon)\cdot\underline{\tau}\right); \ \rho\frac{\partial \dot{\underline{r}}}{\partial t} = \frac{\partial \underline{T}}{\partial \underline{S}}; \ \underline{T} = E\varepsilon\underline{\tau}, \tag{1}$$

where $\underline{r}$ - is the radius-vector of the cable point, S - natural coordinate along the cable, $\underline{T}$ - tensile force, ε - strain, E - Young's modulus, $\underline{\tau}$ - unity vector tangential to the cable.

b) fighter motion:

$$M_{Fighter}\ddot{\underline{u}}_{Fighter} = \underline{T}\left(s_{Fighter},t\right) + \underline{F}_{Fighter}\left(t\right) + \underline{F}_{friction}. \tag{2}$$

c) blocks rotation:

$$J^k_{block} \, \dot{\omega}^k_{z\,block} = M^k_{friction}, \quad k = 1..49 . \tag{3}$$

d) movable carriage motion:

$$M_C \, \ddot{y}_C + B(y_C, \dot{y}_C)\dot{y}_C + C(y_C)y_C = \sum_{i=1}^{36} T(s_i, t) . \tag{4}$$

Here 36 is the number of blocks in the block-and-tackle, subscript "C" denotes the movable carriage, coefficients of the hydraulic elements viscosity and stiffness B and C are depending on the displacement and velocity of the carriage due to the feedback between the carriage motion and closure of the control valve.

e) Coulomb friction between the cable and blocks:

$$F_{friction} = \left[\mu_d + (\mu_s - \mu_d)e^{-c|v|} \right] F_N . \tag{5}$$

An exponential interpolation function smoothes the transition between the static μ_s, and dynamic μ_d coefficients of friction; v is the relative cable/block velocity, c – decay coefficient.
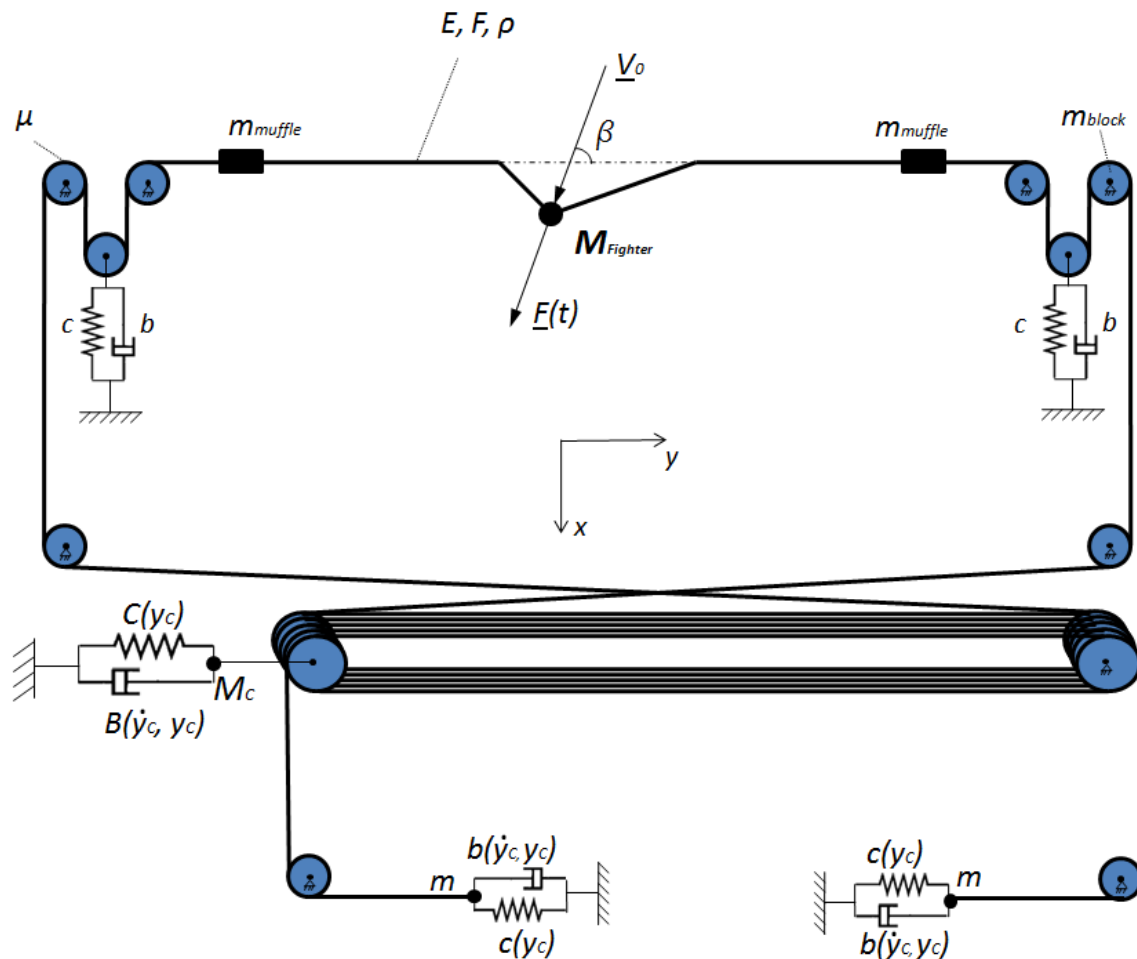
Figure 4. Arresting gear design model
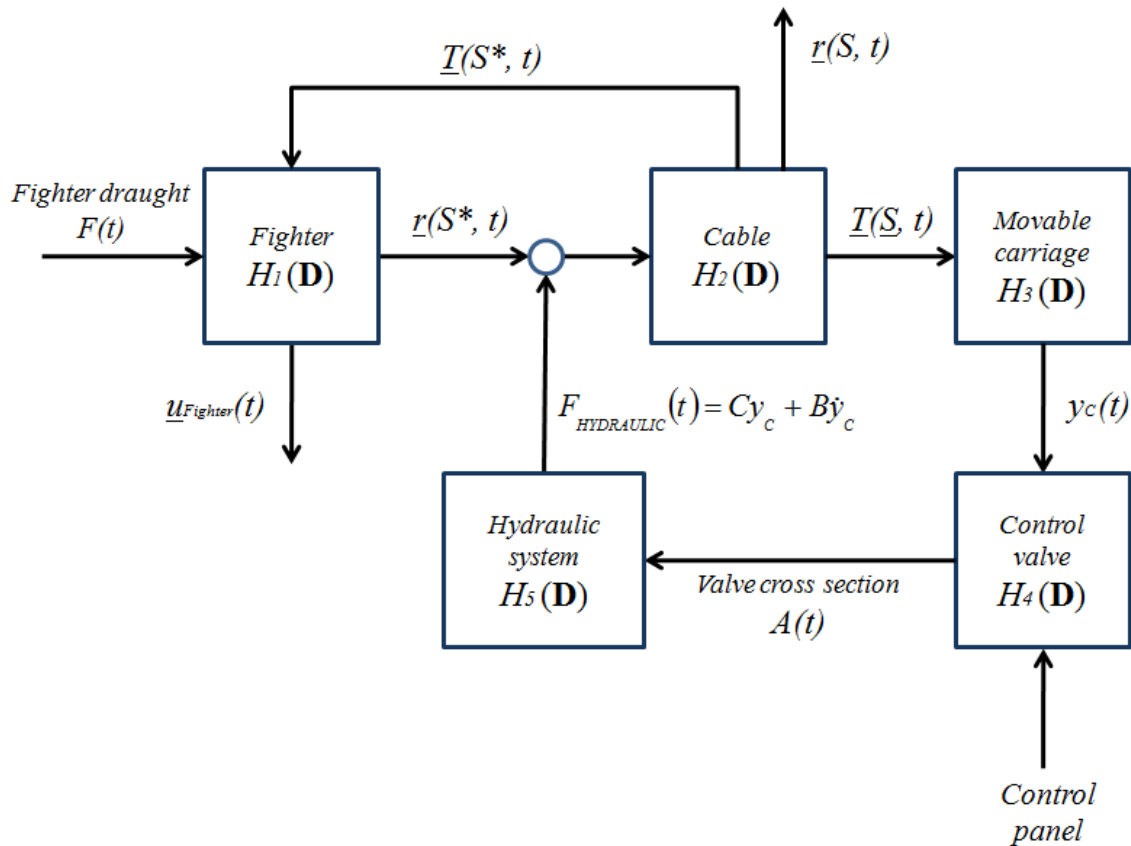
Figure 5. Structured block diagram of the arresting gear

4   LS-DYNA finite element model

The mathematical model described in the previous paragraph cannot be analyzed analytically due to its complexity. So, finite element method and LS-DYNA software were chosen for numerical simulation of the arresting gear. First of all the CAD model based on the real prototype of the arresting gear was developed (Figure 6).
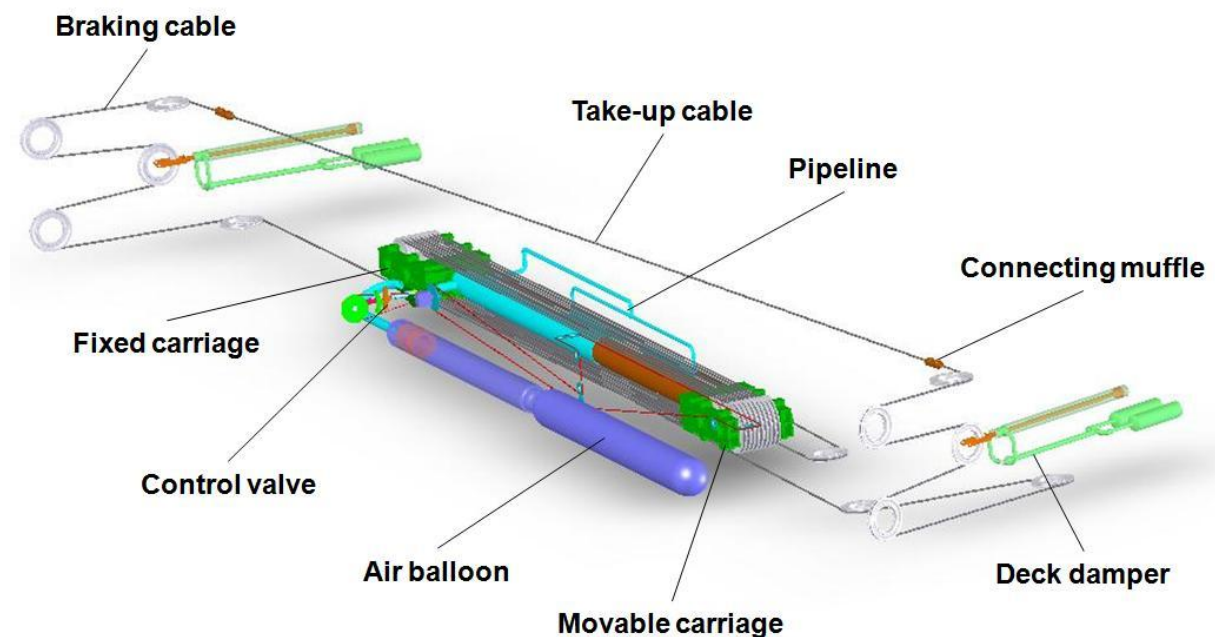

Figure 6. CAD model of the arresting gear

Finite element LS-DYNA model (Figure 7 - Figure 9) is created based on the CAD data. The cable is simulated with use of cable finite elements, based on traditional beam element formulation with eliminated bending terms in the stiffness matrix, and *MAT_CABLE_DISCRETE_BEAM material model. Between take-up and braking cables the connecting muffles, 30 kg each, are placed. The muffles are simulated as rigid bodies. Inclusion of the muffles into the model is important as they reflect longitudinal and transverse waves traveling in the cable. Between the cable and each block the possibility of contact interaction is provided by *CONTACT_NODES_TO_SURFACE card. All the blocks are considered as rigid bodies as their strength is not the point of analysis, but include all the geometrical features to simulate correctly the contact interaction with the cable. Dynamic friction coefficient between the blocks and the cable is taken to be 0.3. FE model also includes spring-damper finite elements based on *MAT_NONLINEAR_ELASTIC_DISCRETE_BEAM and *MAT_DAMPER_NONLINEAR_VISCOUS material models, whose constants are found from a separate hydraulic system analysis performed in ANSYS/CFX. It should be noted that these characteristics are complex expressions, depending on the positions and velocities of the arresting gear parts. As standard capabilities of LS-DYNA code don't include the option for implementation of such dependencies, simulation is done with use multiple restarts, and the new damping and stiffness parameters of the hydraulic elements are re-calculated at each restart step (*CHANGE_CURVE_DEFINITION card is used). Aircraft is simulated by means of a rigid body having the dimensions of a hook, and the mass of a full aircraft. Contact interaction with possible sliding is provided between the aircraft hook and the take-up cable. FE model in total contains 14236 cable elements, 63408 solid elements and 118953 nodes.
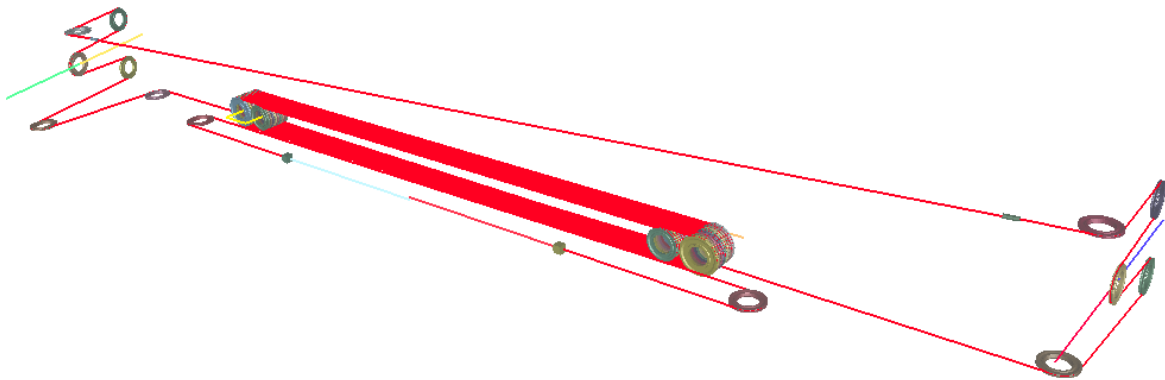

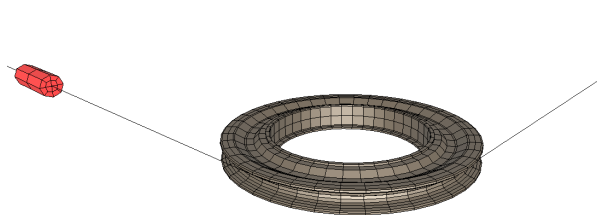*Figure 7. Arresting gear LS-DYNA model*
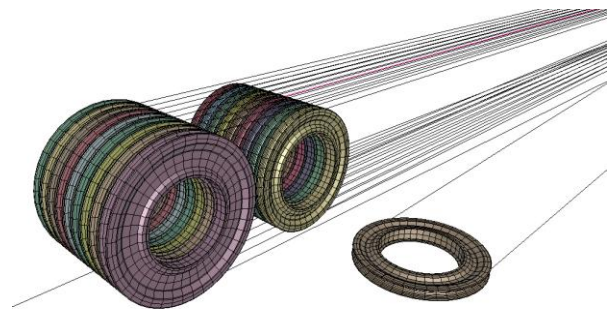

Figure 8. Block and connecting muffle

Figure 9. Block-and-tackle

Taking into consideration the feedback in the arresting gear system, the finite element equations of dynamics looks as the following:

$$\mathbf{M\ddot{u}} + \mathbf{B(u,\dot{u})\dot{u}} + \mathbf{C(u)u} = \mathbf{f}(t,\mathbf{u},\dot{u}). \tag{6}$$

Right-had part of the equations – external loads vector **f** – is depending on time (due to the fighter draught), and components of the cable and blocks nodal displacements and velocities vectors (due to contact interaction with friction). Left-part matrixes of damping **B** and stiffness **C** are depending on the displacement and velocity of the carriage. To take into consideration all these phenomena a Delphi code (see Figure 10 for the algorithm) is developed that allows to control the solution flow and make LS-DYNA restarts with user-defined frequency ΔT.
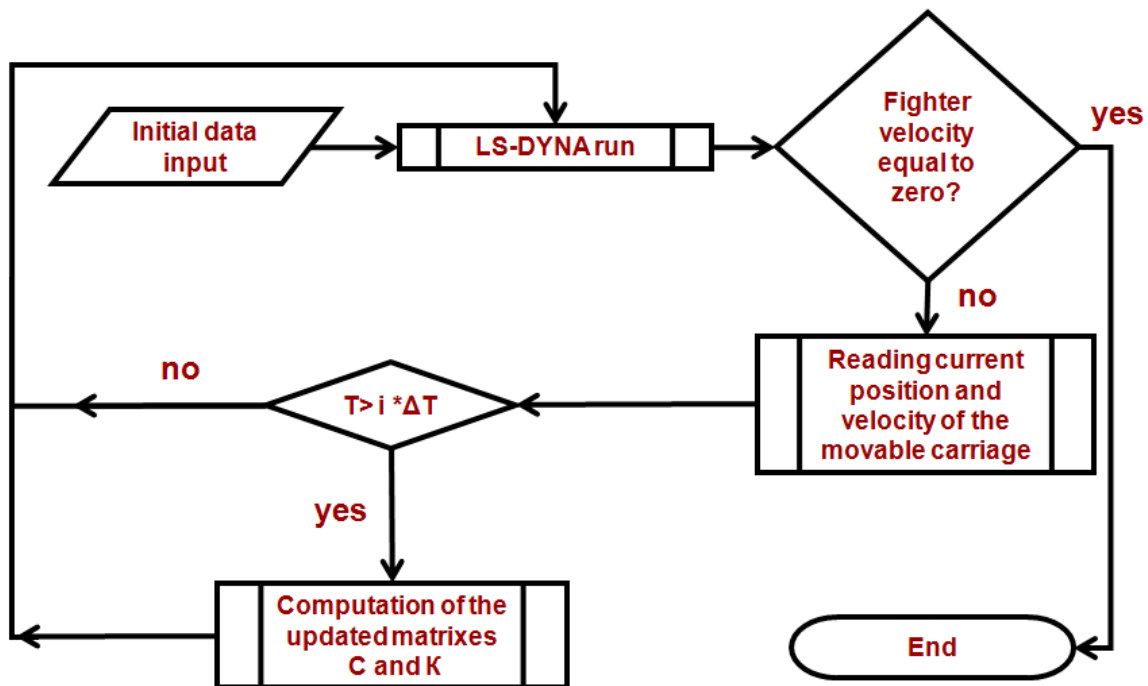
Figure 10. Block diagram of the computation procedure

In order to validate the developed model, a trial simulation was performed for the aircraft of mass 14 ton with initial velocity 240 km/h. Basic criteria for the validation of the model were: deformed shape of the cable, landing time and plot of force (pressure) in the hydraulic cylinder vs. time. The latter can be considered as an integral criterion for both the LS-DYNA FE model and Delphi code, because pressure in the hydraulic system is computed based on results of the dynamics solution and formula obtained from CFD analysis and included into the Delphi code. The deformed shape of the cable and arresting gear elements obtained for the trial run is presented in Figure 11 for different moments of time and fully corresponds to experimental observations.
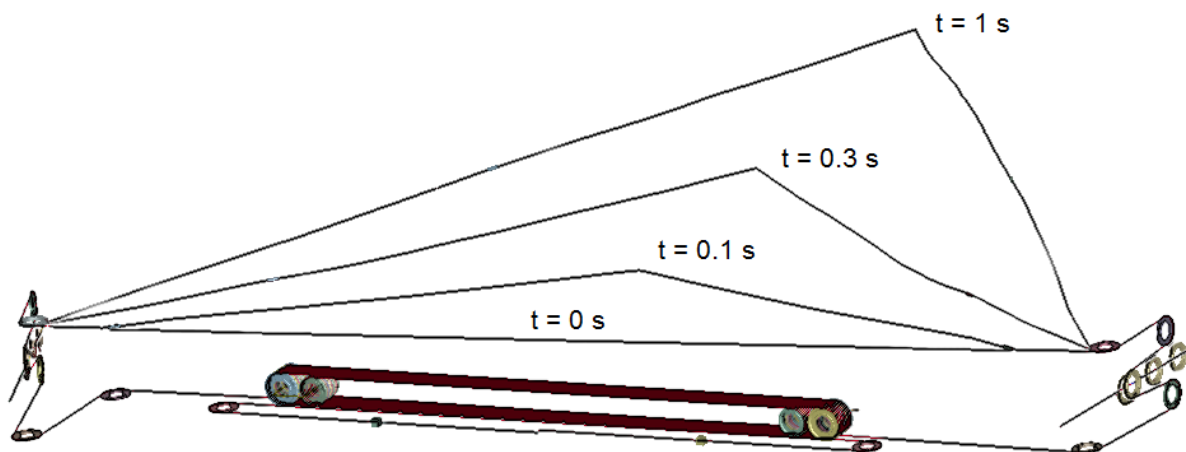

Figure 11. Deformed shape of the arresting gear cable

Plots of pressure in the hydraulic cylinder vs. time obtained from LS-DYNA simulation and taken from real experiment are shown at Figure 12. The difference between two curves does not exceed 10% and may be explained by the facts that not all parameters of the real landing were known (such as the draught vs time).
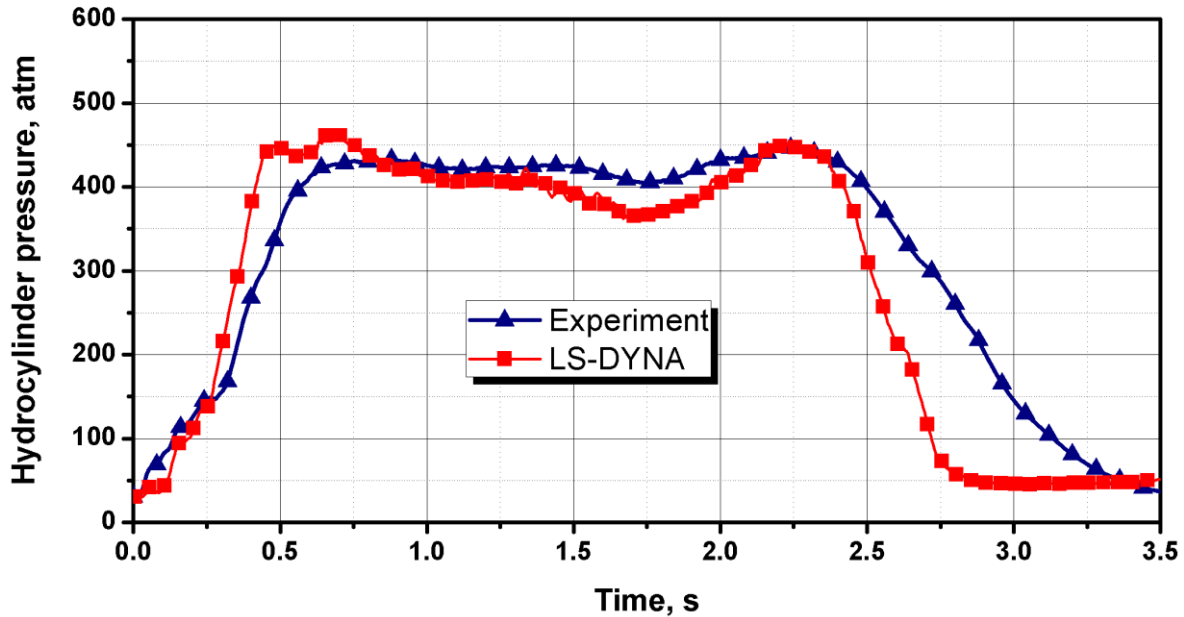
Figure 12. Pressure in the hydraulic cylinder: experiment vs simulation

The conclusion about good correspondence between real arresting gear and the developed LS-DYNA model can be done. Thus the model can be applied for multi-variant analysis of the arrestments with different parameters.

5 Simulation and analysis of landings with different parameters

As it was mentioned above, the arresting gear should be "tuned" for the arrestment of aircrafts with different masses and velocities. For a range of these parameters it should provide optimal (from the point of safety and strength points of view) deceleration with the lowest tension forces in cable and absolute deceleration values for the pilot.

Landing velocity of the aircraft is one of the most important parameters of arrestment, and it can vary in a wide range between 180 and 240 km/h. Analysis of the arresting gear dynamic behavior depending on the velocity is a matter of interest. With the use of developed model analysis for three different landing velocities 180, 210 and 240 km/h (keeping fighter mass and all other parameters constant) was carried out. Plots for comparative analysis of results are presented at Figure 13 - Figure 16.
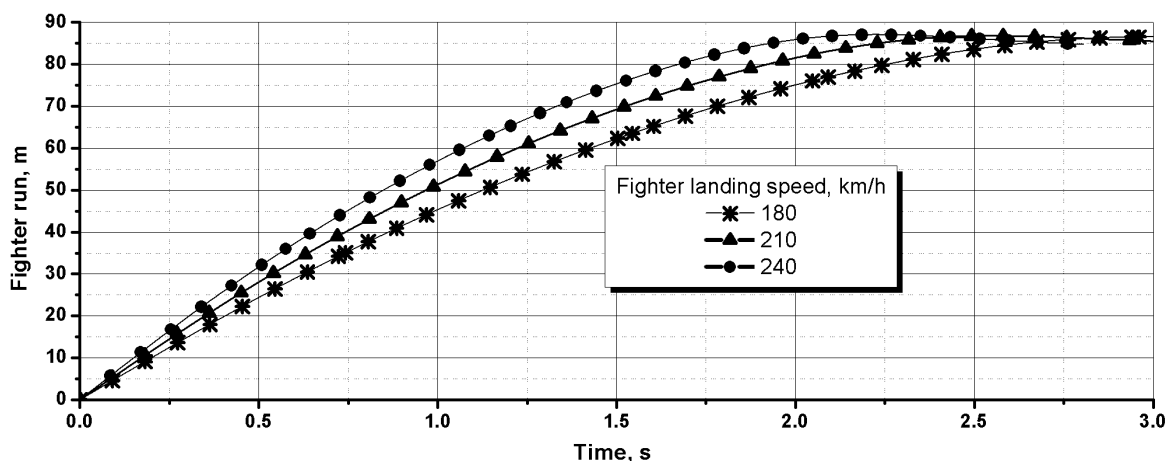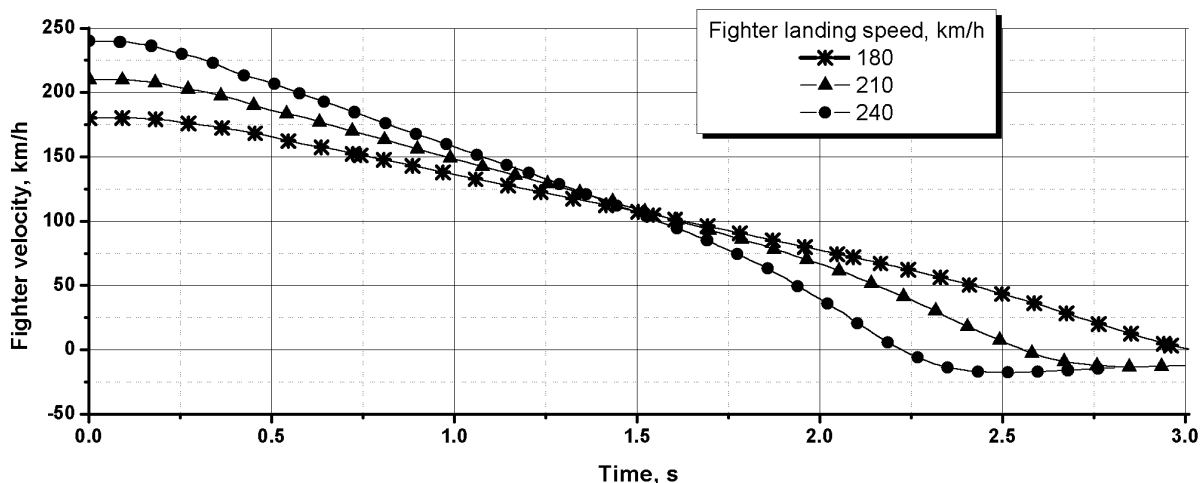

Figure 13. Fighter run

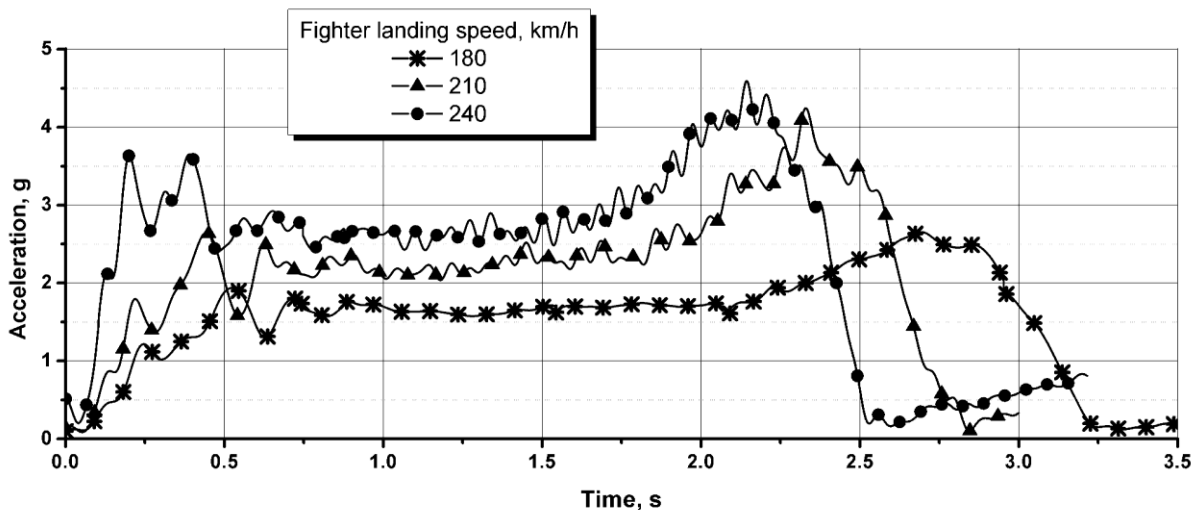*Figure 14. Fighter velocity during landing*
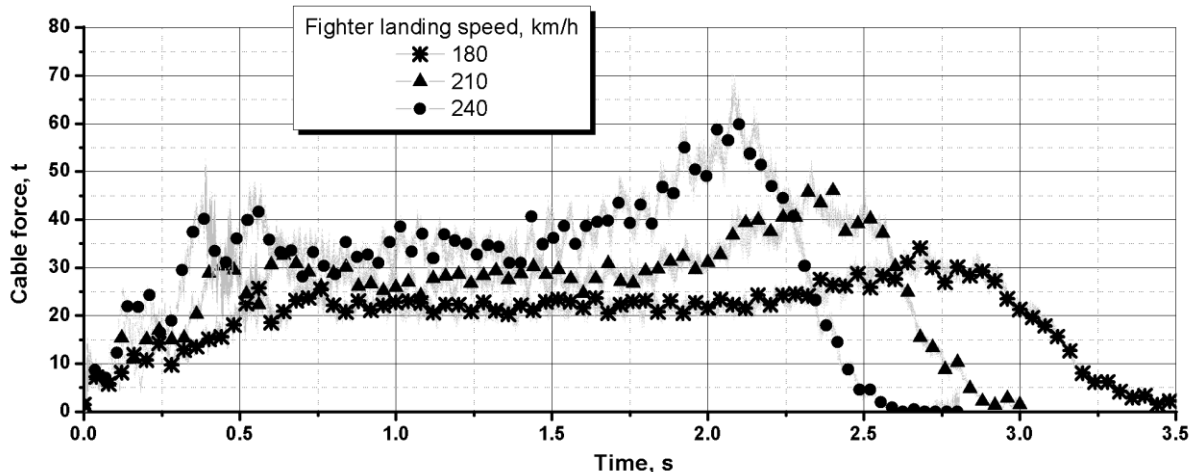

Figure 15. Fighter deceleration

Figure 16. Force in the cable near the hook

6   Conclusions

In the current paper the results of applied research and simulation of the arresting gear dynamics are presented. Arresting gear mathematical and computational models are developed and simulation of

the fighters arrestments with different parameters is carried out. The presented model was used for optimization of the arresting gear and verification of the new design concepts.

7   Acknowledgments