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

Dmitriy Mikhaluk
Mechanics and Control Processes Department
St.Petersburg State Polytechnical University
Russia
Mikhaluk@CompMech.spbstu.ru
Tel./fax: +7 (812) 552-7778
Mobile: +7 (921) 744-1755

Igor Voinov
Mechanics and Control Processes Department
St.Petersburg State Polytechnical University
Russia
Voinov@CompMech.spbstu.ru

Alexey Borovkov, Prof., Dr.
Mechanics and Control Processes Department
St.Petersburg State Polytechnical University
Russia
Borovkov@CompMech.spbstu.ru

Abstract

In the current work a full-scale dynamic model of the deck arresting gear is developed. Arresting gear is a special aero-carrier unit that is destined to provide efficient arrest of deck jet-fighters with high deck landing speed (200-240 km/h). It consists of a hydraulic plunger brake connected with take-up cable stretched across the deck, through the multiple block-and-tackle and spring-damper elements. The developed numerical model contains all basic elements of the real prototype and used to analyze the dynamic behavior of the arresting gear and tune it for specific conditions of the arrest.

Keywords

Arresting gear, cable, dynamic analysis, FEA

1 Introduction

Jet-fighters deck landing is one of the most complex and critical parts of the flight. It requires failure-free operation of the arresting gear system and skilled actions of the pilot. One of the factors that influences safety of the deck landing is the strength of the arresting gear structural elements and optimal “tuning” of the system for the arrest of the jet-fighter with specific mass moving with specific velocity.

Statement and solution of mechanical problems for such complex systems is extraordinary complex, as the phenomena to be described are highly non-linear and though require application of modern technologies.

Currently for development of competitive high-tech devices most of the companies use science-intensive computer-aided technologies to solve highly non-linear mechanical problems. These technologies are based on simultaneous application of fundamental knowledge of applied mechanics and modern numerical methods and procedures, finite element method first of all [Zienkiewicz O.C., Taylor R.L. (2000)].

In the current paper the problem of development, validation and utilization of mathematical and numerical models of arresting gear is solved. The developed model is applied for simulation and analysis of landings with different parameters.

2 Operational principles of arresting gear

Arresting gear is a unit installed on a deck of aero-carriers and providing arrest of jet-fighters during landing. Arresting gears operational scheme is constantly developing since beginning of 20th century. Till 1927 gravity-based arresting gears were in use. Kinetic energy of the arrested fighters was converted into work for translation of sandbags laying on the deck. Then friction-based arresting devices appeared. Starting from 1937 on most carriers there were installed hydraulic arresting gears – prototypes of the modern devices.

Now arresting gear (Fig. 1) represents a hydraulic plunger braking machine, connected through block-and-tackle and system of blocks and dampers to a take-up cable that is stretched across the deck [Matveenko A.M. (1984)].

Figure 1. Arrestment

The cable consists of two parts – take-up cable and braking cable. During deck landing the jet-fighter grasps the take-up cable with a hook. The take-up cable is coupled with the braking cable that is designated to transfer jet-fighter pull to the hydraulic braking machine. The latter is represented by hydro-cylinder and accumulator where the kinetic energy of the fighter is transferred to the heat and then dissipated.

Arresting gear is equipped with control system. Using control arm one can set the device for the arrest of specific mass. Due to this system arresting gear guarantees equal braking distance for a variety of aircraft masses. Control valve in the hydraulic system is changing the flow area during the landing and though influences the braking deceleration. When the fighter is stopped, the cable gets released and arresting gear returns to the initial condition ready for next arrest, during 30 seconds. The return to initial condition is done due to saved energy in the air accumulators.

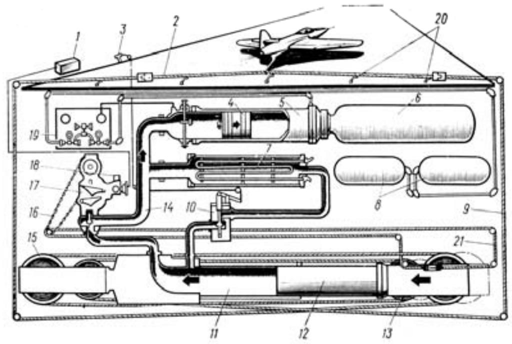

Figure 2. Arresting gear scheme.
2 – take-up cable; *4* – accumulator piston; 5 – accumulator; *6* – air balloon; *9* – braking cable; *11* – hydraulic cylinder; *12* – plunger; *13* – movable carriage; *14* – pipeline; *15* – fixed carriage; *17* – valve; *18* – fighter mass selector

3 Mathematical model

When saying about mathematical modeling normally scientists distinguish between two types of modeling [Myshkis A.D., Blehman I.I., Panovko Ya. G. (1983)]. The first type is fundamental. It implies development of general models that are applicable for a wide class of solutions. Material models, failure models, etc are models of the first type.

Second type is applied modeling. This type of modeling is used in the current research. Development of the mathematical model of the arresting gear and subsequent simulation can be divided into the following four stages:

- Mathematical formulation of the problem;
- Choosing the method;
- Numerical computations and validation of the model;
- Multiple simulation runs and analysis of results.

First two stages require both fundamental and applied knowledge of mechanics. Last two stages require much time. So, the developed model should be both adequate and feasible for multiple analysis runs in terms of CPU time spent.

At the first stage of arresting gear analysis the real prototype was examined and solid models were created for further analysis. It was understood that the problem is highly non-linear and high-speed, and general equations of dynamics together with equations for the wave motions in strings can be applied for analysis. Contact interaction between blocks and cable should be considered as well. At this stage several test cases were solved for the string dynamics using both analytical formula [Rakhmatulin H.A. (1947), Craggs J.W. (1954)] and finite element method. Applicability of the latter was proved for the given type of the problem – transverse impact of a body to a string (cable) taking into consideration complex constraining, shape and mass of the impacting body, angle of impact.

During creation of mathematical model of the arresting gear it is important to define what parameters should it include, and what processes should it describe. A series of models was developed during the current research:

- hydraulic system model to describe pressures and flow velocities in the pipelines and hydro-cylinders;
- kinematical systems and control valve model to describe movement of cam, levels and valve itself;
- dynamic model to describe displacements, velocities and accelerations of arresting gear parts, cable forces and motion of aircraft.

Development of the latter, dynamic model is a quintessence of the whole research, because it includes the results obtained with use of the first two models, and it serves to get main parameters of arresting gear and aircraft motion.

For development of the sequence of models the following methods and tools were used:

hydraulic model – computational fluid dynamics approach based on finite volumes method and implemented in ANSYS/CFX software;

kinematical model – direct integration of equations of motion with use of finite differences method implemented in MSC.ADAMS software.

dynamic model – finite element (FE) method together with central difference explicit integration method implemented in LS-DYNA software [Hallquist J.O. (1998)]. This model is described below in more details.

When using FE method for consideration of dynamics the system of differential equations is brought to a high order system of algebraic equations:

$$\mathbf{M}\ddot{\mathbf{u}} + \mathbf{C}\dot{\mathbf{u}} + \mathbf{K}\mathbf{u} - \mathbf{f} = \mathbf{0}, \qquad (1)$$

where **M** – mass matrix, **C** – damping matrix, **K** – stiffness matrix, **f** – external forces vector.

To solve this system in time the central difference method is chosen [Dokainish M.A., Subbaraj K. (1989)]. Considered period of time is divided into increments *Δt* and recurrent scheme is applied to find solution at the moment $t_n = t_{n+1} + \Delta t$.

To extend solution from step *n* to step *n+1* vectors of external forces **f** and stress divergence vector $\mathbf{P} = \mathbf{C}\dot{\mathbf{u}} + \mathbf{K}\mathbf{u}$ are computed and then acceleration vector **a** may be found as:

$$\mathbf{a}^n = \mathbf{M}^{-1}(\mathbf{f}^n - \mathbf{P}^n). \quad (2)$$

After that velocity and displacement is calculated:

$$\mathbf{v}^{n+1/2} = \mathbf{v}^{n-1/2} + \mathbf{a}^n \Delta t^n, \quad (3)$$

$$\mathbf{u}^{n+1} = \mathbf{u}^n + \mathbf{v}^{n+1/2} \Delta t^{n+1/2}, \quad (4)$$

where

$$\Delta t^{n+1/2} = \frac{\Delta t^n + \Delta t^{n+1}}{2}. \quad (5)$$

Nodal coordinates are updates as

$$\mathbf{x}^{n+1} = \mathbf{x}^0 + \mathbf{u}^{n+1}. \quad (6)$$

During time integration every time step is computer using Courant–Friedrichs–Lewy condition (CFL condition) providing stability of solution. For cable element this time step can be found as follows:

$$\Delta t_c = \frac{L_e}{c}, \quad (7)$$

where c – adiabatic velocity, L_e – length of element (in actual configuration). Minimum time step among all finite elements is selected for the whole model:

$$\Delta t^{n+1} = a * \min(\Delta t_1, \Delta t_2, ..., \Delta t_n). \quad (8)$$

If during creation of mathematical and numerical model one takes adequacy as a basis, it could lead to a very close-to-reality model, but so complex that the problems would be never solved. In the current research a compromise between adequacy and complexity was found. Simulation of the arresting gear dynamics during the whole landing process (3 seconds) takes about 20 hours using Intel Core2Duo workstations, and requires 2 Gb RAM and 20 Gb of HDD space. But at the same time due to high level of adequacy the result of simulation includes all motion parameters of all arresting gear elements, cable forces and motion, hydraulic system pressures and flow velocities, aircraft motion parameters.

4 Finite element model and its validation

To perform analysis of the arresting gear during landing of aircrafts of different masses and moving with different velocities finite element model was created.

Take-up and braking cables were simulated with use of special cable finite element, based on traditional beam element with eliminated bending terms in the stiffness matrix.

Between take-up and braking cables there exist connecting muffles, 30 kg each. These muffles are simulated as rigid as their strength is not the point of analysis. Inclusion of these muffles into the model is important as they reflect longitudinal and transverse waves traveling in cables.

Cable comes through a system blocks and 18x block-and-tackle. Blocks in the block-and-tackle are installed on two carriages – movable and fixed. In total there are 48 blocks in the model. Between each block and cable, possibility of contact interaction is provided by chosen numerical algorithm [Oldenburg M., Nilsson L. (1994)]. Movable carriage is rigidly connected with the piston of main hydro-cylinder and on the other hand via feedback – with control valve. During arrestment cable is pulled by the aircraft and movable carriage runs to fixed, fluid is forced out from the hydro-cylinder through the control valve and at the same time its flow area is reducing, increasing resistance of the valve and guaranteeing controlled deceleration of the aircraft.

All blocks are considered as rigid bodies as their strength is not the point of analysis, but include all geometrical features to simulate contact interaction with cable in a correct way. Dynamic friction coefficient between blocks and cable is taken to be constant and equal to 0.3.

Dynamic FE model also includes dampers (damper of braking machine, deck dampers and cable end dampers) that are simulated as spring-damper finite elements, whose characteristics were found earlier in hydraulic analysis. It should be noted that these characteristics are nonlinear and depend on position and velocities of arresting gear parts. As standard capabilities of LS-DYNA code doesn't include option for implementation of such dependencies, simulation is done with multiple restarts and new damping and stiffness parameters of hydraulic elements are re-calculated each restart step.

General view and fragments of the developed model are shown in Fig. 3 – 6.

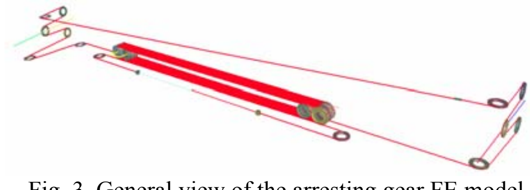

Fig. 3. General view of the arresting gear FE model

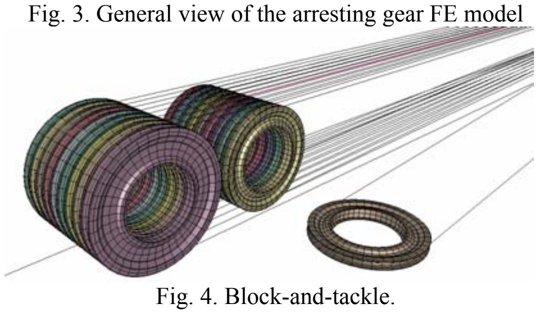

Fig. 4. Block-and-tackle.
Blocks installed on the movable carriage.

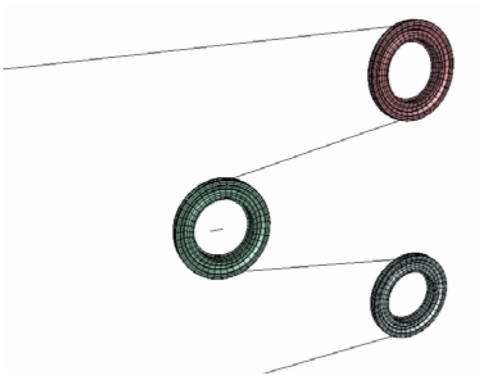

Fig. 5. Deck damper

Fig. 6. Deck block and muffle

Aircraft is simulated by means of point mass at a cable, with sliding capabilities.

In order to verify adequacy and validate developed model, trial simulation was performed for the aircraft of mass ***m*** with initial velocity ***V***. Basic criteria for the validation of the model were: general dynamics behavior and deformed shape of the cable; landing time and plot of pressure in the main hydro-cylinder vs time. The latter can be considered as integral criterion for the whole FE model and feedback, because pressure in the hydraulic system is computed based on results of the dynamics solution and formula obtained from CFD analysis.

Deformed shape of the cable and arresting gear elements obtained for the trial run is presented in Fig. 7 – 9 for different moments of time.

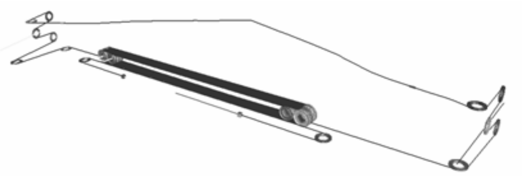

Fig. 7. Deformed shape. T=0.5 s

Fig. 8. Deformed shape. T=1.5 s

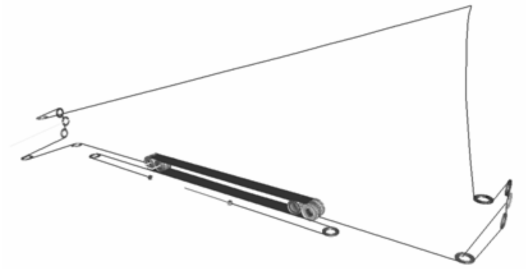

Fig. 9. Deformed shape. T=2.5 s

Plots of pressure in the main hydro-cylinder vs time obtained from FE simulation and taken from real experiment are shown below in Fig. 9. It can be seen, difference between two curves is almost negligible. Small difference (not exceeding 5%) may be explained by the fact that not all parameters of the real landing were known.

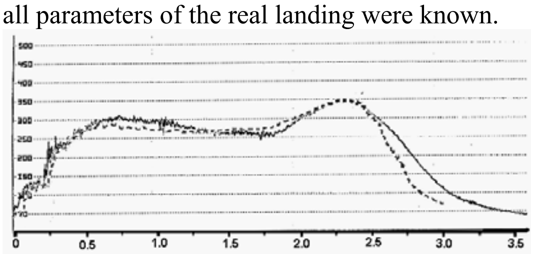

Fig. 10. Pressure in hydro-cylinder vs time:
- - - - FE simulation —— Experiment

So, the conclusion about full correspondence between real arresting gear and developed numerical model can be done. Thus the model can be applied for multi-variant analysis of the arrestments with different parameters.

6 Simulation and analysis of landings with different parameters

As it was mentioned above, arresting gear can be "tuned" for 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) deceleration with the lowest forces in cable and absolute deceleration values for the pilot.

Mass of the aircraft is one of the most important parameter of arrestment, and it can vary in a wide range between 10 and 30 tons. Analysis of arresting gear dynamic behavior depending on the mass is a matter of interest.

With the use of developed model analysis for three different masses 10, 20 and 25 tons (keeping velocity and all other parameters constant) was carried out.

Plots for comparative analysis of the cable forces in the take-up cable and pilot decelerations are presented in Fig. 11 – 12.

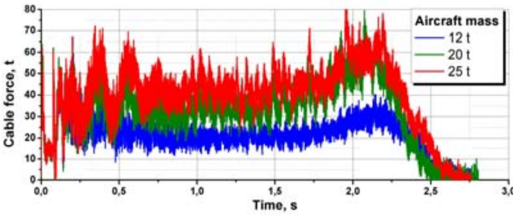

Fig. 11. Cable force

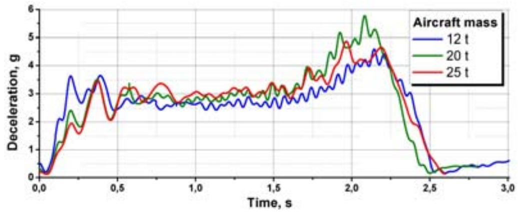

Fig. 12. Deceleration curves

Another parameter of interest is the initial velocity of the aircraft. Analysis of three landings with velocities 180, 210 and 240 km/h was carried out.

Plots for comparative analysis of the aircraft velocities, cable forces and pilot decelerations are presented in Fig. 13 – 15.

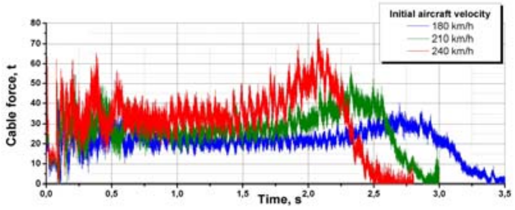

Fig. 13. Cable force

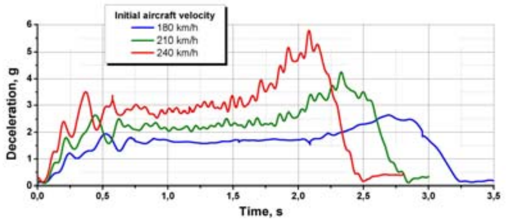

Fig. 14. Deceleration curves

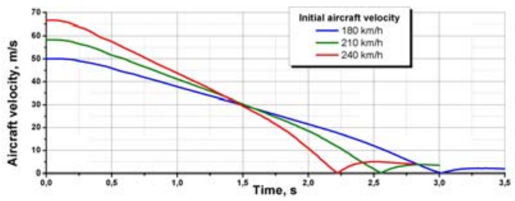

Fig. 15. Deceleration curves

It can be concluded that for aircraft with higher initial velocity arrestment time is longer, and deceleration at the second stage of landing is higher than those for the aircraft with lower initial velocity.

Conclusions

In the current paper the results of applied research and simulation of arresting gear dynamics are presented. Arresting gear mathematical and computational models are developed with use of modern numerical methods and simulation of aircraft arrestments with different parameters is done. The presented model was used for optimization of the arresting gear and verification of new design concepts.

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References

Craggs J.W. (1954). Wave motion in Plastic-Elastic strings. *Journ.of the Mech and Phys of Solids,* vol. 4.

Dokainish M.A., Subbaraj K. (1989). A survey of direct time-integration methods in computational structural dynamics – I. Explicit methods. Computers and Structures, vol. 32, No.6, pp. 1371-1386.

Hallquist J.O. (1998). LS-DYNA. Theoretical Manual. Livermore Software Technology Corporation.

Matveenko A.M. (1984). Aerodrome arresting units. Moscow, Mashinostroenie. (in Russian).

Myshkis A.D., Blehman I.I., Panovko Ya. G. (1983). Mechanics and applied mathematics. Logics and application peculiarities. Moscow, Nauka. (in Russian).

Oldenburg M., Nilsson L. (1994). The position code algorithm for contact searching. *Int J for Numerical methods in Eng*, vol. 37, pp. 359-386.

Rakhmatulin H.A. (1947). On the impact to flexible string. *Applied mathematics and mechanics*, vol. 11, № 3.

Zienkiewicz O.C., Taylor R.L. (2000). The finite element method. Vol. 1. Butterworth Heinemann.