

On Modeling of Ejection Process in a Training Combat Aircraft

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Abstract

The paper deals with modeling and simulation of motion trajectory of an ejection seat in the training-combat aircraft TS-11 "Iskra". The ejection seat and its operation are characterized. Mathematical and computer models are elaborated with the help of MATLAB-Simulink applications. Additionally, simulations are conducted for various velocities of the aircraft.

Keywords: aircraft, ejection, ejection seat, simulation

Nomenclature

a, b	– object mass centre coordinates – bottom pair of rollers [m],
$c = \arcsin(\delta - \chi)$	– a distance of the mass centre from bottom rollers [m],
$C_{za}, C_{xa}, C_m = f(\alpha)$	– coefficients of lift, drag force and a pitching moment of the object,
$d = \sqrt{a^2 + b^2}$	– a component of the mass centre distance from bottom pair of rollers [m],
$g = 9.81$	– the acceleration of gravity [m/s ²],

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h	– a plane flight height [m],
I_y	– an inertia moment of the object in relation to y coordinate [$\text{kg}\cdot\text{m}^2$],
n	– G-force affecting the object during launch,
$\rho_0 = 1,168$	– an air density for $h=0\text{m}$ [kg/m^3],
$\rho = \rho_0 \left(1 - \frac{h}{44300}\right)^{4,256}$	– an air density for $0 \leq h \leq 11000\text{m}$ [kg/m^3],
P_x, P_z, M	– a drag and lifting force, a moment pitching the object [$\text{kg}\cdot\text{m}/\text{s}^2$, $\text{kg}\cdot\text{m}^2/\text{s}^2$],
S	– an object cross-section [m^2],
$Q = mg$	– an object gravity force [$\text{kg}\cdot\text{m}/\text{s}^2$],
$t_{pr} = 0.01875$	– the time of the seat movement in the guides on down pair of rollers [s],
V	– an object flying speed [m/s],
V_x	– a speed component of the level flight of the object [m/s],
V_z	– a speed component of the vertical flight of the object [m/s],
V_s	– a plane flying speed [m/s],
V_0	– a speed of launch [m/s],
$\alpha(0) = \chi - \gamma$	– an angle of attack of the object, during movement on guides [rad],
θ	– an object angle of inclination [rad],
γ	– an angle of inclination of the object flight path [rad],
χ	– an angle of inclination of the seat guides [rad],
ω_y	– an angular velocity of the object [1/s].

1. Introduction

Initial models of ejection seats were used in planes during the second World War (WW II). A pilot after leaving the plane with the help of an ejection seat, was separated from the plane and then he landed using a parachute. However, increasing flight velocities often caused a failure of the system due to collisions with a tail-plane. Since then the rescue systems were constantly improved in order to ensure the safety during positive or negative overloads. According to statistics, since the ejection seat was invented, about 16000 pilots have been saved throughout the world.

In modern aircrafts, the British ejection seats of the company Martin Baker and the Russian seats of the company ZWEZDA are used successfully. During many air shows, pilots had the opportunity to present to the public a performance of the seat at a very low height. In most cases, the pilots suffered with no injuries during an ejection. This demonstrates the high-quality, fully automated and applicable construction of these seats. The task of the pilot in this case, is to achieve an appropriate flight level and to initiate the ejection process. In the absence of a control of the aircraft, a board computer calculates the trajectory of the ejection seat in order to prevent a collision with the earth.

The ejection seats may be divided into the following four generations [3]:

- I. Generation I – elaborated between 1940–1965. Their operation based on an compressed air, a rocket motor or a pyro-cartridge. Such seats were developed in order to throw out the pilot outside the limits of the plane. In the first version of these ejection seat a pilot manually opened a parachute (e.g. Saab Mk – 1 and Martin Baker Mk 1- 5 seats).
- II. Generation II – developed between 1965–1975. The racket motor was improved, decreasing the possibility of pilot injuries. The last version of ejection seats of this generation allowed to exploit them at a zero flight speed (e.g. Martin Baker Mk – 7 and the Douglas seats).
- III. Generation III – from 1975 till today. The sensors and gyroscope mechanisms were implemented in order to regulate a seat position according the flow of the wind. The board computer calculated the time of opening of a rescue and braking parachute according to a weight of the pilot (e.g. Russian ejection seat K-37-800 from 1992, Martin Baker Mk – 14 seats).
- IV. Generation IV – used at present. Electronic control systems determining ejection parameters are still improved in these seats (e.g. ejection seat K-36D-3,5 used since 2001).

2. Problem Description

2.1. Plane – object configuration model

The plane model together with the object is examined in the coordinate system xz , so the plane rolling is not taken into consideration.

According to the terminology accepted in literature [6], the four coordinate systems are implemented (Fig. 1):

- the static system Oxz ,
- the plane system $O_Sx_Sz_S$,
- the object system $O_Fx_Fz_F$,
- the system connected with the direction of flowing streams $O_Fx_a z_a$.

The plane under consideration is moving with a constant velocity V_S , in a level flight with a constant flight height. The object is considered as a solid body. After

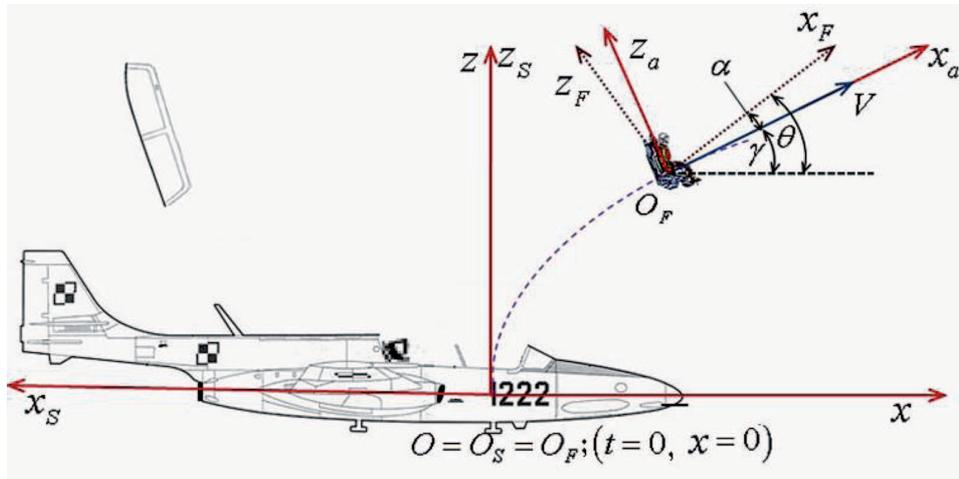


Fig. 1. The plane and object coordinate system

an ejection initiation, the object starts to move on the guides with a speed V_0 and an acceleration G -force n under an angle χ . In Fig. 2 the forces and moments affecting the moving object are shown.

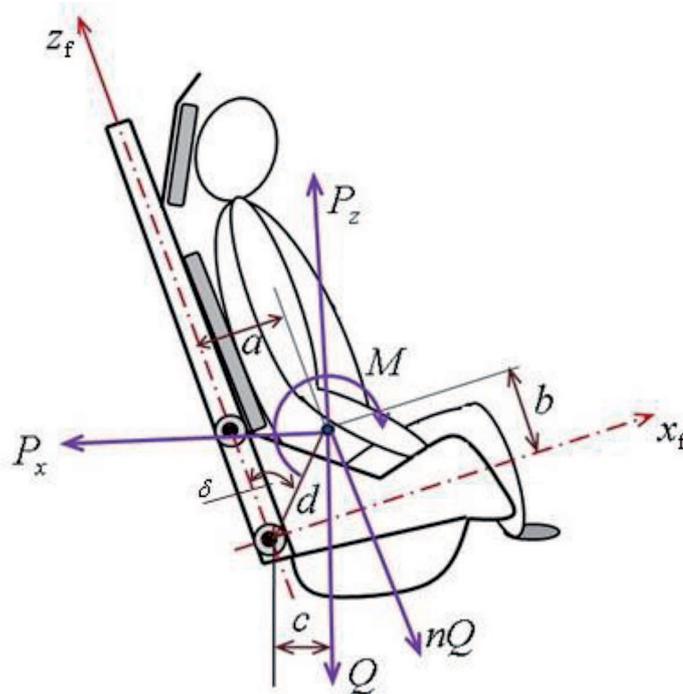


Fig. 2. The forces and moments affecting the object

After leaving the guides, the vertical component of the object motion is affected by initial ejecting conditions, the G-force and an aerodynamic force component. The level component is dependent on the initial velocity and the air resistance. Additionally, due to the aerodynamic moment, the object starts to rotate with an angular velocity ω_y .

The problem is that the seat must clear the tail of the plane. The seat must be climbing at a high enough speed for the plane to pass underneath it. Drawing a triangle from the second seat position to the top of the tail gives the seat path, minimum vertical distance and horizontal distance. For TS-11 aircraft, pilots are 1,5 m below the tail, but also 5,50 m away (the second pilot), an angle of 15 deg, and 6,5 m away (first pilot), an angle of 13 deg.

2.2. Equations of the object motion

The equations of motion are elaborated on the basis of paper [3,6]. The initial velocity of the object at the moment of leaving the guides reads

$$V(0) = \sqrt{V_x^2 + V_z^2} = \sqrt{(V_S - V_0 \sin \chi)^2 + V_0^2 \cos^2 \chi}. \quad (1)$$

The initial angle of inclination of the object track is

$$\sin \gamma = \frac{V_z}{V} = \frac{V_0 \cos \chi}{V}, \quad \gamma = \arcsin \frac{V_0 \cos \chi}{V}. \quad (2)$$

The components of the aerodynamic forces (the lift and the drag) and the object aerodynamic moment are as follows

$$\begin{cases} P_z = 0.5\rho V^2 C_{xa} S, \\ P_x = 0.5\rho V^2 C_{za} S, \\ M = 0.5\rho V^2 C_m S l. \end{cases} \quad (3)$$

During the motion on the guides the seat is affected by 3 torques

$$\begin{cases} M_1 = 0.5\rho V^2 S (C_m l + C_{za} (a \cos \alpha - b \sin \alpha) + C_{xa} (b \cos \alpha + a \sin \alpha)), \\ M_2 = Qna, \\ M_3 = Qc. \end{cases} \quad (4)$$

The torques cause a turn of the seat of the angle

$$\Delta\theta = \frac{M_1 - M_2 - M_3 \frac{t_{pr}^2}{2}}{I_y + md^2}. \quad (5)$$

2.3. Mathematical model of the object

The object under consideration has 3 degrees of freedom. The equations of motion of the object read

$$\left\{ \begin{array}{l} m\dot{V} = -P_x - Q \sin \gamma, \\ mV\dot{\gamma} = P_z - Q \cos \gamma, \\ \dot{x} = V \cos \gamma, \\ \dot{z} = V \sin \gamma, \\ \dot{\theta} = \omega_y, \\ \dot{\omega}_y = \frac{M}{I_y}. \end{array} \right. \quad (6)$$

The equations are solved by means MATLAB-Simulink packages with the following initial conditions: $h=250$ m, $V=250, 400$ and 650 km/h. Accessible data in literature were used for modeling.

2.4. Example of real SK ejection seat

Polish armed forces exploit aircrafts equipped with ejection seats of III and IV generation, with some exceptions like “Iskra” TS-11. This jet trainer was developed by Prof. Tadeusz Sołtyk in 1960, and since 1962 is being exploited by Polish Air Forces. The basic technical data of this two – person crew (a pilot and a trainee) aircraft are as follows [5]:

- the length – 11,15 m,
- the wing span – 10,06 m,
- the height – 3,5 m,
- the lifting area – 17,5 m,
- the kerb mass – 2560 kg,
- the total weight – 3724 kg (version SNP),
- the max. starting weight – 3838 kg,
- the maximum speed – 720 km/h.

TS-11 „Iskra” is equipped in two identical ejection seats of I generation (Fig. 3), which are classified as light seats (56 kg together with a parachute) [6]. These seats are fixed in a cockpit with by means of a special mechanism and two guide bars.

SK seats are composed of a frame together with a parachute unit (the rescue parachute S-3 series 2M, weight – 20 kg), a headrest, a backrest and fasten belts – 50 mm (back, hip, crotch). Additional elements are: a release control mechanism, a releasing mechanism (with the pyro-cartridge PK-4-1), a belts adjustment mechanism, a safety protection releasing handle and the AD-3 automat located at the right side of the seat (a delay time of releasing belts is 1,5 s). The reason of the PK-4-1 implementation is to achieve the trajectory that exclude a collision with a tail-plane. According to [5], the pilot is the first of the crew to be evacuated. The minimum



Fig. 3. SK ejection seat (without parachute)

height for the ejection is 250 m with the speed $V_s=350-400$ km/h, recommended for the level flight of 600 m, and for the down-flight of 1000 m. During a takeoff, up to 250 m, and during landing, the pilot has no chance to leave the plane in a normal way. The only way out for the crew is to land in an accidental area. There are a few positive ejecting procedures in a height limit 250-600 m in the history of TS-11 planes (e.g. 1995 – $h=480$ m, in 1987 – $h=250$ m). But there were situations that despite of the flight height over 250 m, the pilot did not survive, in 2005 – $h=290$ m). Therefore, the aim of the paper is to examine this type of the ejection seat.

The sequence of the ejecting procedure follows from [5]. During ejecting, the pilot should use two hands, shifting inward two levers of the cockpit shield that activates the releasing mechanism. Then resting his hands on the armrests, the pilot presses the lever of a seat launch. Because the parachute is located in the ejecting seat, after ejecting the pilot has to push himself out the seat. In the case when the pilot after ejecting is still keeping the launch lever, what may be caused by a disorientation resulting from a seat rotation or a collision with the tail-plane, there is a possibility that the height is insufficient for opening the rescue parachute. The rescue parachute is equipped in the automatic device KAP-3P with the time delay of 2 s and at the minimum opening height 2400 m. The device is designed to initiate the opening of the parachute, after the pilot separates from the ejection seat for a distance of 1,5 m and releases a parachute pin. The time delay is necessary for separating the pilot on a safe distance from the seat after opening the parachute, as well as the falling seat to avoid to collide with the pilot or with the parachute. In the further parts of this paper, the configuration of the ejection seat and the pilot is called the object.

2.5. Computer simulation model

The computer model is elaborated with the help of the block method (Fig. 4). Aerodynamic features being functions of a varying angle of approach during the motion on a trajectory, are accepted on the basis of [4,7] and implemented in their analytical shape.

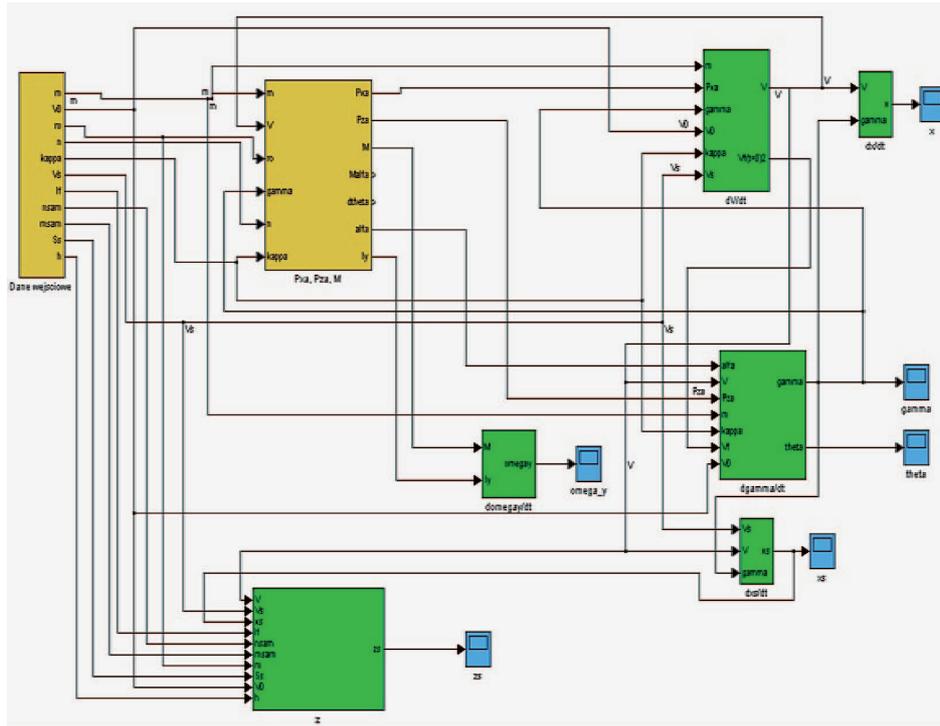


Fig. 4. Computer simulation model

The seat mass and inertial data were determined in the experimental way. The aircraft TS-11 ejection seat (number H-1244) was used in calculations. The individual components of the seat have been disassembled to most possible extent, and then detailed measurements (a length, a width, a thickness and a weight of items) have been carried out. Then, their models in a computer program CADD (Computer-aided design and drafting) have been developed. The next step was to assemble the individual parts numerically and to obtain a spatial model. The use of CADD software allowed to obtain exact masses and inertial data for the ejection seat.

The simulation procedure is as follows. The user enters the speed and the flight altitude of the aircraft and the simulation time is set. There is a possibility to change the mass of the pilot and the ejection speed (depending on the type of a pyro –

cartridge) used. The program automatically calculates G-force affecting of the pilot during the ejection. The results generated by the program can be presented in a form of graphs and tabular data.

3. Results

The object characteristics were analyzed at the minimum height of 250 m. An increase of the flight velocity results in a decrease of the height of the object flight above a vertical height tail-plane (Fig. 5).

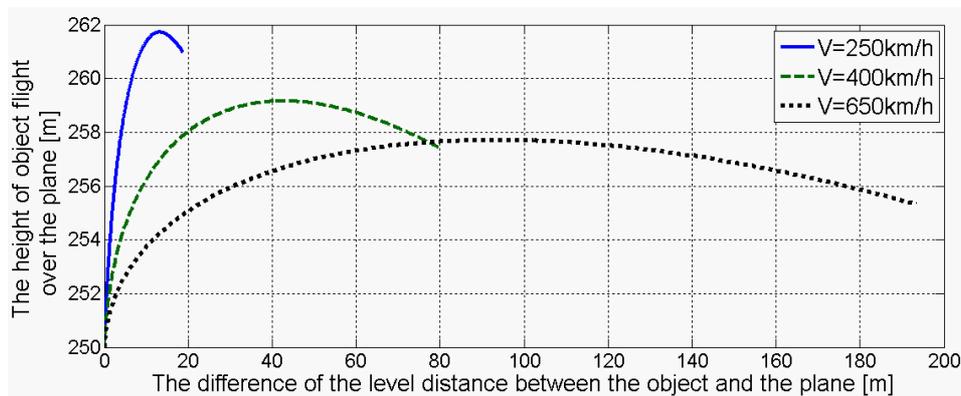


Fig. 5. Trajectory of the object over the plane (h=250 m, t=2 s)

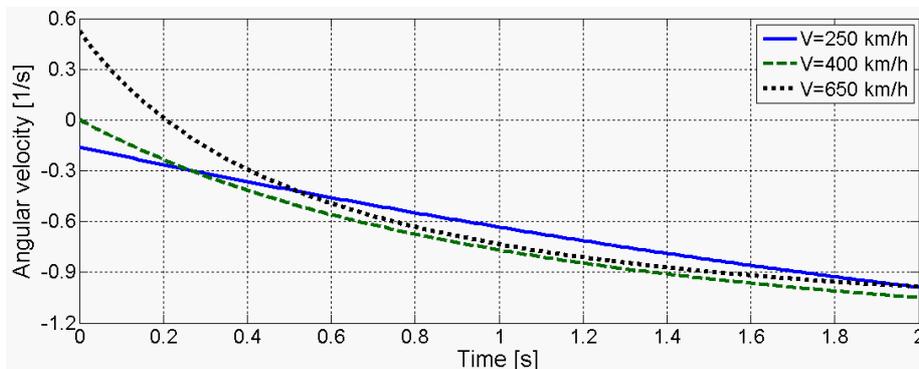


Fig. 6. Variation of angular velocity ω_y in time

The recommended speed that ensure the object flight over the tail-plane with a reserve of 2,5-3 m is 350-400 km/h, with the seat inclination $\theta = -30$ deg. In this case the object flies with the directed in to the tail-plane bottom side of the seat front part. At the moment of 1.5 s after ejection, the object is in a safety distance

of 50 m behind the plane and the automatic device AD-3 is activated. The seat inclination γ angle at this moment is equal to -2 deg. The inclination object angle during 1 s changes in a range from 100 deg to 150 deg, depending on the flight speed.

In Fig. 6. and Fig. 7. a variation of the angular velocity and an angle of the inclination in time are shown. At the moment of 2 s after the ejection angular velocities are almost the same for different ejecting speed.

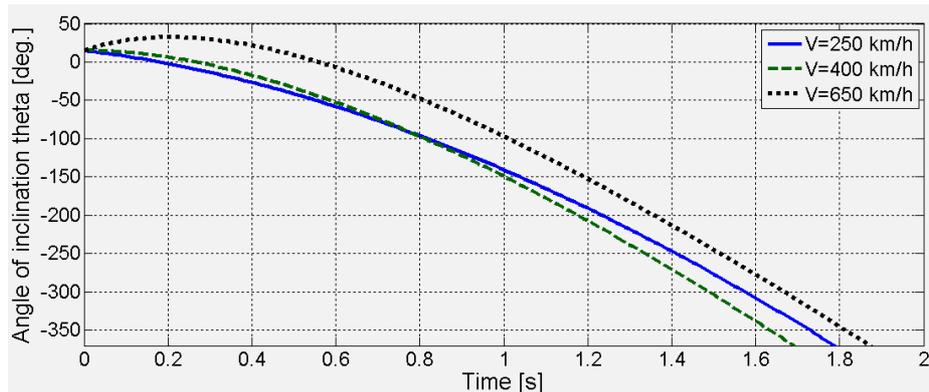


Fig. 7. Variation of the angle of inclination θ in time

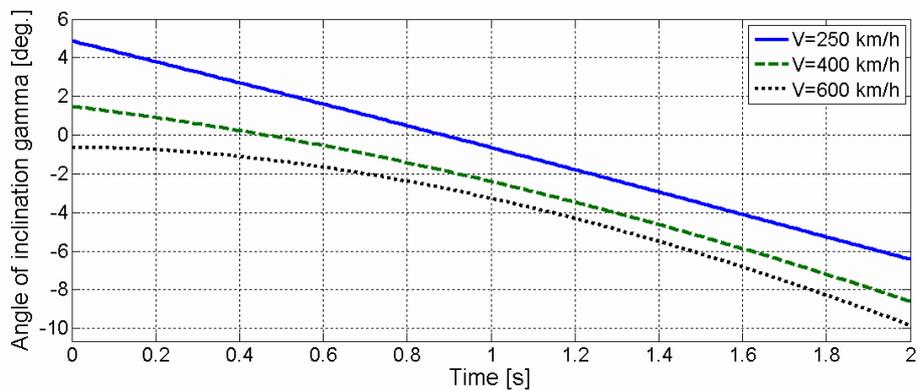


Fig. 8. Variation of the trajectory angle of inclination γ in time

4. Conclusions

A crew evacuation from a disabled aircraft is one of the basic problems in aviation. Despite of the technological progress, there is no ejection seat that ensures

absolute safety of the pilot at any height and speed. Even the best seat of IV generation, during the ejection launch at a low height, requires the inclination angles and the vertical speed component vector to be equal to zero. Any violations of these conditions increase the value of permissible height of safety ejecting.

Exploited at presence ejection seats ensure the safe separation from a plane in specific conditions. One of them is the minimal ejection height – 250 m. One has take into consideration that even at this height the ejection process might fail. Due to the seat rotation, the G-force and an improper ejection angle, there is a possibility of collision of the object with the tail-plane. One of the important factors is the various mass of pilots, that can have an influence on the object moment of inertia.

The modification of the ejection TS-11 seat or making it the e-seat 0-0 class (height – 0, speed – 0) would improve crew safety but there are some obstacles. Firstly, the costs of modern seat implementation is unprofitable, because of the value of the plane. Secondly, the application of a seat of bigger mass than SK would influence the balance of the plane, and there could be necessity of conducting expensive tests increasing the value of the plane.

Taking into consideration the fact that these planes would stay in Polish Air Forces for a couple of future years, it is recommended to analyze the pilot-seat system and its features with the help of CFD (Computer Fluid Dynamics) methods. Additionally the tests in an aerodynamic tunnel are recommended. The development of the ejection seat model and their the 3D-dynamics is necessary. The tests should consider such factors as: a sideslip, a plane torsion, overloads and wind conditions. The ejection simulation at various phases of the flight (like a tailspin) makes it possible to gain more information and to increase the consciousness, reliability and efficiency of the system performance.

The model developed by means of Matlab-Simulink packages and the results obtained, can be used by a person operating an aircraft equipped with the ejection seats of the first generation. However, the sophisticated behavior of the modern ejection seats having thrust nozzles and other mechanisms cannot be evaluated using such a model. However, several planes are in use, include these by private persons worldwide. Knowing of the ejection seat trajectory is essential in analyzing a failed ejection. A lack of knowledge of the physics of the phenomenon can lead to a disaster [1]. The model presented can be considered as a starting point for developing better understanding of the pilot ejection process.

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