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Simulation of trajectory of an aircraft seat ejection

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. The ejection seats may be divided into the following four generations [2]:

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.
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.
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).
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).

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 [4]:

- 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.

2 SK ejection seat in TS-11 „Iskra"

2.1 Construction of the SK ejection seat

TS-11 „Iskra" is equipped in two identical ejection seats of I generation (Fig.1), which are classified as light seats (56 kg together with a parachute) [5]. These seats are fixed in a cockpit with by means of a special mechanism and two guide bars.

Fig. 1. SK ejection seat (without parachute)

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 [4], the pilot is the first of the crew to be evacuated. The minimum height for the ejection is 250 m with the speed Vs=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).

The sequence of the ejecting procedure follows from [4]. 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.

2.2 Article terms list

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],

h – a plane flight height [m],

I_y – an inertia moment of the object in relation to y coordinate [kg·m^2],

n – G-force affecting the object during launch,

$\rho_0 = 1{,}168$ – an air density for h=0 m [kg/m^3],

$\rho = \rho_0 \left(1 - \frac{h}{44300}\right)^{4{,}256}$ – an air density for $0 \le h \le 11000$ m [kg/m^3],

P_x, P_z, M – a drag and lifting force, a moment pitching the object [kg·m/s^2, kg·m^2/s^2],

S – an object cross-section [m^2],

$Q = mg$ – an object gravity force [kg·m/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].

2.3 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.

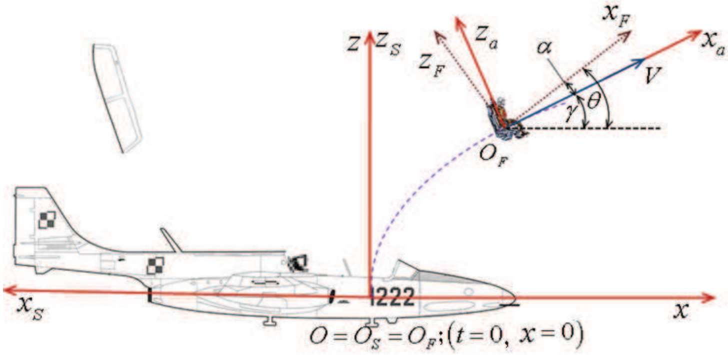

Fig. 2. The plane and object coordinate system

According to the terminology accepted in literature [5], the four coordinate systems are implemented (Fig. 2):

- the static system Oxz,
- the plane system $O_S x_S z_S$,
- the object system $O_F x_F z_F$,
- the system connected with the direction of flowing streams $O_F x_a z_a$.

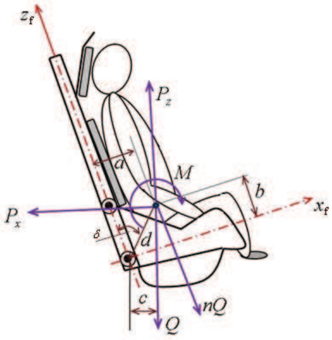

Fig. 3. The forces and moments affecting the object

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 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. 3. the forces and moments affecting the moving object are shown.

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.

2.4 Equations of the object motion

The equations of motion are elaborated on the basis of paper [2,5]. The initial velocity of the object at the moment of leaving the guides reads

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

The initial angle of inclination of the object track is

$$\sin\gamma=\frac{V_z}{V}=\frac{V_0\cos\chi}{V}, \qquad \gamma=\arcsin\frac{V_0\cos\chi}{V}. \tag{2}$$

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

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

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

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

The torques cause a turn of the seat of the angle

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

2.4 Mathematical model of the object

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

$$\begin{cases} m\dot{V}=-P_x-Q\sin\gamma, \\ mV\dot{\gamma}=P_z-Q\cos\gamma, \\ \dot{x}=V\cos\gamma, \\ \dot{z}=V\sin\gamma, \\ \dot{\theta}=\omega_y, \\ \dot{\omega}_y=\dfrac{M}{I_y}. \end{cases} \tag{6}$$

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.

2.5 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 of basis [3,6] and implemented in their analytical shape, while the seat mass features are taken according to paper [1].

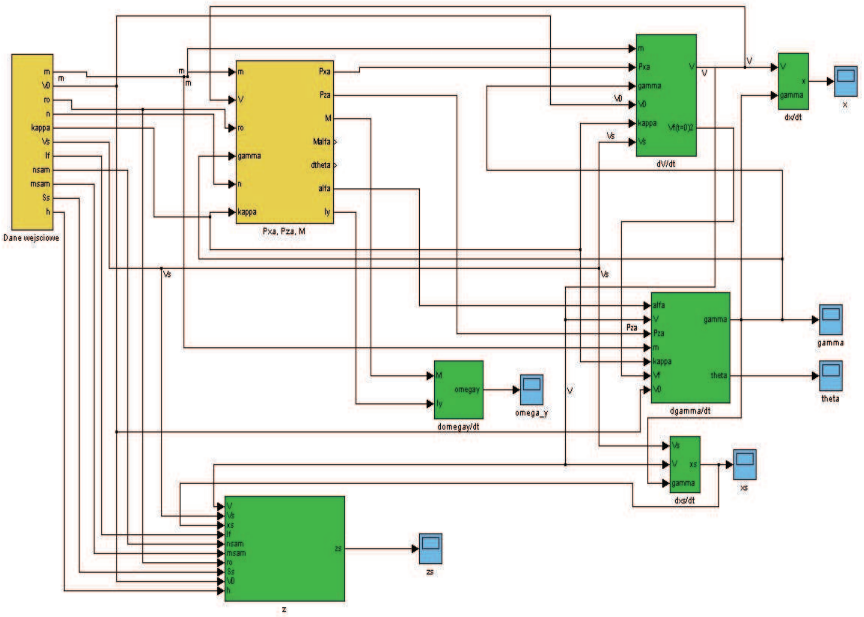

Fig. 4. Computer simulation model

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).

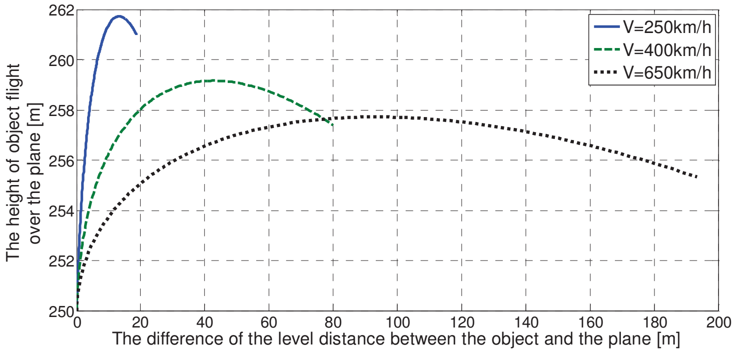

Fig. 5. Trajectory of the object over the plane (h=250m, t=2s)

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 θ = -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 50m 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 to 150 deg, depending on the flight speed.

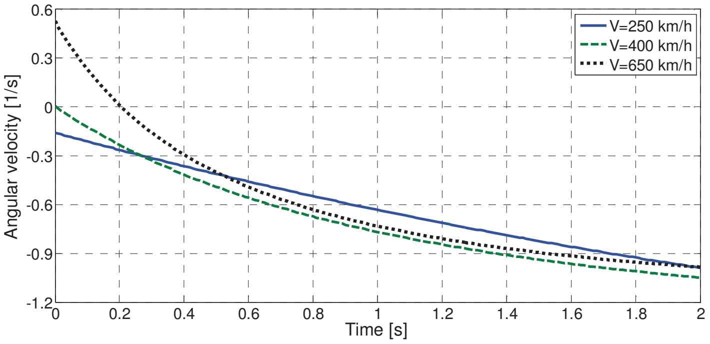

Fig. 6. Variation of angular velocity ω_y in time

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 2s after the ejection angular velocities are almost the same for different ejecting speed.

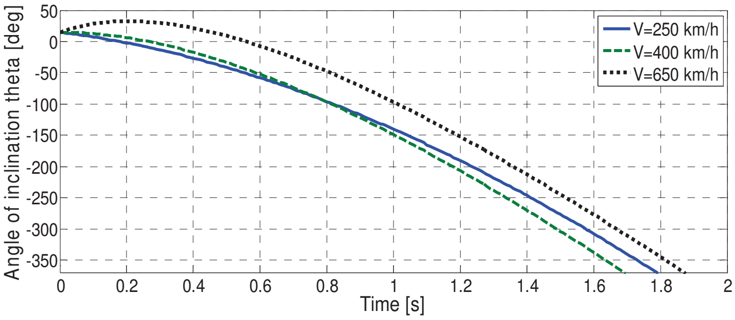

Fig. 7. Variation of the angle of inclination θ *in time*

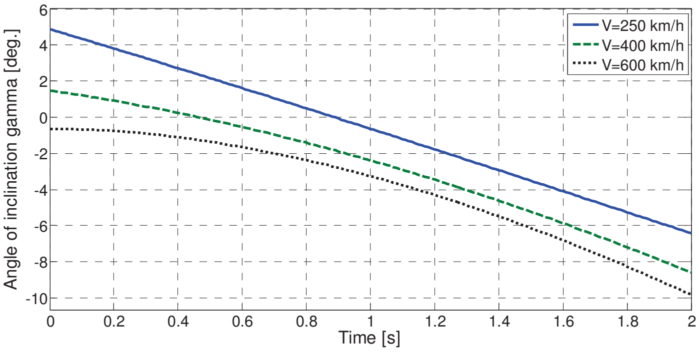

Fig. 8. Variation of the trajectory angle of inclination γ *in time*

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 interia. Results can be used successfully to other aircraft, which are equipped by similar type of ejection seat.

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 then 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.

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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.

Trajektorie lotu fotela katapultowego samolotu odrzutowego

Streszczenie

W artykule przedstawiono dynamikę fotela katapultowego o nazwie SK na podstawie odrzutowego szkolno-bojowego samolotu TS-11 „Iskra”. Scharakteryzowano fotel katapultowy i zasadę jego działania. Opracowano model matematyczny oraz komputerowy obiektu przy wykorzystaniu programu MATLAB – Simulink i przeprowadzono symulację przy różnych prędkościach lotu.