MODELLING OF THE EJECTION PROCESS IN A SYMMETRICAL FLIGHT

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This paper presents a mathematical model of the ejection seat trajectory in a symmetrical design. The component speeds and displacements of the seat in function of time are determined by means of an analytical method. The model takes into account the change of air density in function of height and the change of free fall acceleration dependent on the latitude and flight height of the seat. The gravity load that acts on the pilot in the chest-back direction in function of the flight height and speed is determined. The mathematical model with the initial conditions is used for creation of a computer application with the use of MATLAB software, owing to which it was possible to obtain the flight trajectory of the seat in relation to the aircraft and in relation to the ground. The minimum distance which the seat flows over the vertical stabilizer depending from the pilot's mass and the aircraft speed is determined.

Key words: modelling of ejection, pilot safety, trajectory of ejection seat

1. Introduction

One of the crucial issues related to the flight of an aircraft is the problem of rescuing human life in an emergency. When an aircraft is inefficient, the pilot is forced on many occasions to leave the cockpit and to land safely on the ground. The parachute is the primary device to achieve this purpose. However, in order to use its potential, one needs to depart from the aircraft to a safe distance.

In the past, when the aircraft was maneuverable, the pilot by reversing the aircraft along its longitudinal axis and by moving the control stick "away from himself" used the negative gravity load and performed a centrifugal ejection from the cockpit. If there was no maneuverability, insofar as the gravity load permitted this, the pilot would leave the cockpit by jumping over its side. The development of aeronautical engineering and an increase of speeds of aircraft used has resulted in danger of collision during such a maneuver with the vertical stabilizer. Hence, the device has been introduced known as the ejection seat.

Attempts to develop a mathematical model of an analytical process of ejection are presented in Szendzielorz (1986), were the authors focused on the minimum ejection time that prevents the passage of the seat over the vertical stabilizer. Another dynamical model that is based on the second principle of dynamics are presented in Ramm *et al.* (1994), Machowski and Szajnar (1995), Szajnar and Wojtkowiak (1999).

The purpose of the present article is to develop an analytical model of the flight path of the seat, its simulation taking into account various conditions (a change of the speed and mass of the pilot). It was assumed that the aircraft is moving in a one-level flight (without any rolling).

2. TS-11 aircraft and ejection seat

TS-11 "Iskra" training and military aircraft has been used since the year 1961 by the air forces in Poland and in India. It possesses two identical first generation ejection seats that are classified

as light seats (56 kg including the parachute). They are installed in the cockpit with the aid of a seat firing system and two guide rails, whose task is to give the direction during the ejection. An overall construction of the seat is presented in Fig. 1.
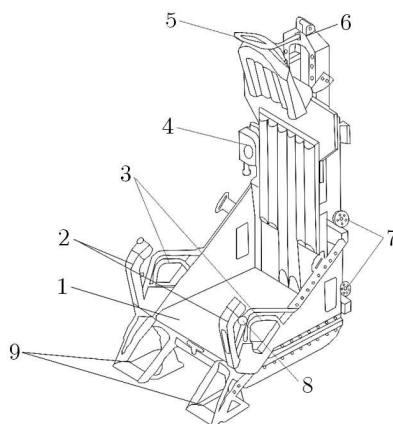

Fig. 1. Chief elements of the SK-1 seat: 1 – parachute, 2 – levers of independent release of the cockpit canopy, 3 – launching levers, 4 – AD-3 timer release unit, 5 – bow to destroy the cockpit canopy, 6 – pyrocartridge in the shot pipe, 7 – upper and lower pair of rollers, 8 – lever that locks belts, 9 – footrests to keep feet during ejection

The minimum ejection height is 250 m with the aircraft speed $V_s = 350\text{-}400$ km/h, while the recommended height is 600 m in the one-level flight and 1000 m in the nose dive [1]. When taking off and landing in the range within 0-205 m, the pilot has no possibility to leave the aircraft with the use of the seat. The minimum height of 250 m makes it possible for the pilot to be saved on condition that the pilot manually opens the lock of the seat belts, pushes himself off from the seat and manually opens the emergency parachute. The PK-4-1 pyrocartridge used to drive the seat ought to ensure such a trajectory which prevents the pilot from hitting the vertical tail unit of the aircraft.

3.   Mathematical model

At the beginning of the discussion, an XY system of coordinates is introduced on a plane determined in a two-dimensional space as follows: the starting point, which is the center of the gravity of the seat, the vector of the seat initial speed and the vector of the earth gravity force (Fig. 2). The vector of speed $\mathbf{V}_0$ is deflected back from the vertical axis by a constant angle κ_f. The vector of the initial speed of the seat $\mathbf{V}_f$ is inclined to the horizontal axis by an angle γ_f and it depends from the speed of the aircraft and the body mass of the pilot. The values of angles κ_f and γ_f will be equal if the aircraft speed is $\mathbf{V}_s = 136$ km/h (accepting that the body mass of the pilot $m = 80$ kg, which corresponds to an acceleration of 18 G). The aerodynamic characteristics of the TS-11 aircraft and the stall speed in a smooth configuration (without the flaps being extended and with the landing gear retracted) is ca. 200-210 km/h (depending on how much fuel is left), hence in a real flight no situation will occur when angles κ_f and γ_f are equal.

The beginning of the coordinate system is set in the center of gravity of the seat (the moment of the upper part of the guidelines installed in the aircraft cockpits is being lowered), the OX axis is in the direction of the speed vector of the flight of the aircraft, the OY axis is directed vertically in the direction that is opposite to the gravitational acceleration vector. The gravitational acceleration value depends on latitude ϕ and altitude above the sea level H [m], and it can be determined from equation

$$g(H) = 9.780327(1 + 0.0053024\sin^2\phi - 0.0000058\sin^2 2\phi) - 3.086 \cdot 10^{-6}H \qquad (3.1)$$
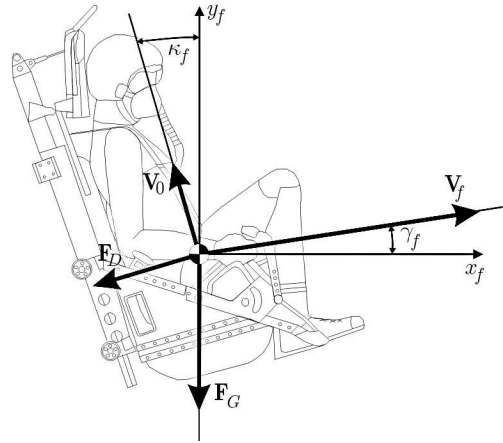
Fig. 2. Forces acting on the seat and velocity vectors in the symmetrical system

If the location of the center of gravity of the seat, as presented in (Fig. 2), is marked as $[x(t), y(t)]$, the vectors at a moment t can be written as follows:

- speed vector $\mathbf{V}_f(t) = [\mathbf{V}_{xf}(t), \mathbf{V}_{yf}(t)]$
- acceleration vector $\mathbf{a}_f = [\mathbf{a}_{xf}(t), \mathbf{a}_{yf}(t)]$
- earth gravity vector $\mathbf{F}_G = [0, -m\mathbf{g}]$
- drag force vector $\mathbf{F}_D = [-\mathbf{F}_{Dx}, -\mathbf{F}_{Dy}]$

It is assumed that the aircraft is moving in a one-level rectilinear uniform flight with $\mathbf{V}_s$ speed. The ejection is realized from cockpit I and cockpit II, where the horizontal distance from the centre of gravity of the seat that is leaving the vertex of the guides to the upper part of the vertical stabilizer is $L_I = 6.32$ m for the first cockpit and $L_{II} = 5.32$ m for the second cockpit (Fig. 3). The total height that is to be reached by the seats is $h = h_1 + h_2 = 2.61$ m. The height h consists of height $h_1 = 1$ m (height of the guides) and $h_2 = 1.61$ m (vertical height from the end of the guides to the upper part of the vertical stabilizer). The inclination angle of the guides is $\kappa_f = 12°$. The vector of speed that is attained by the seat from the pyrocartridge is directed along the guides and its value depends on mass of the pilot's body (Fig. 4).
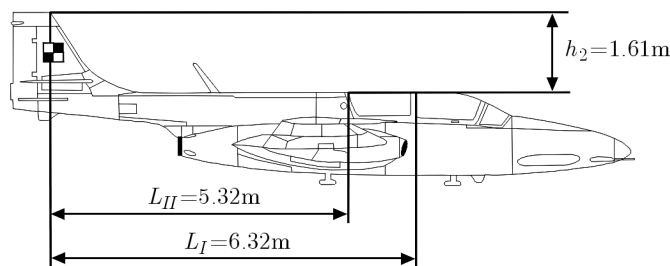

Fig. 3. Distances and height from the seat guides to the vertical stabilizer

At the moment the seat is being ejected from the cockpit, the force acting on the pilot according to the Second Newton's Law can be written as

$$\mathbf{F}_{eject} = m\mathbf{a}_f \tag{3.2}$$

The acceleration can be provided in m/s^2 or in G units, where acceleration 1G means the gravitational acceleration on the sea level, i.e. 1G=9.81 m/s^2. In this case, it is known as a gravity load. The maximum gravity load to which the pilot weighing 80 kg is subject during ejection

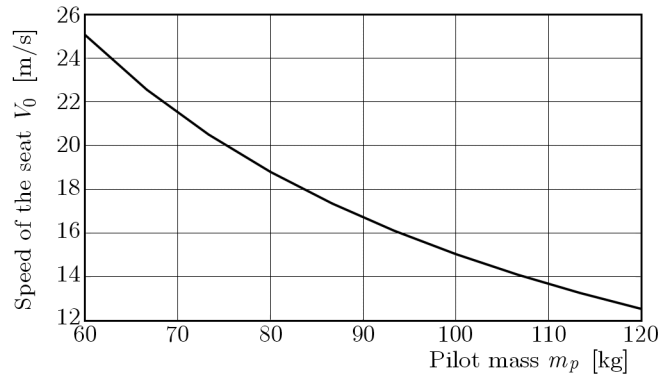Fig. 4. Speed of the seat when leaving the guides depending on the pilot's mass

is $18\,\mathrm{G}$. For this gravity load and mass of the pilot's body including the seat being $136\,\mathrm{kg}$, the acceleration and force acting on the pilot have the following values

$$\mathbf{a}_f = 18 \cdot 9.81 = 176.58\,\mathrm{m/s}^2$$
$$\mathbf{F}_{eject} = m_{136}\mathbf{a}_{f80} = 136 \cdot 176.58 = 24014.88\,\mathrm{N} \tag{3.3}$$

A higher value of the gravity load acting in the same period of time on the pilot with a smaller mass results in a higher probability of the occurrence of compression fracture of the spine. The gravity load that the pilot is subject to from the pyrocartridge in function of the pilot's mass is presented in Fig. 5.
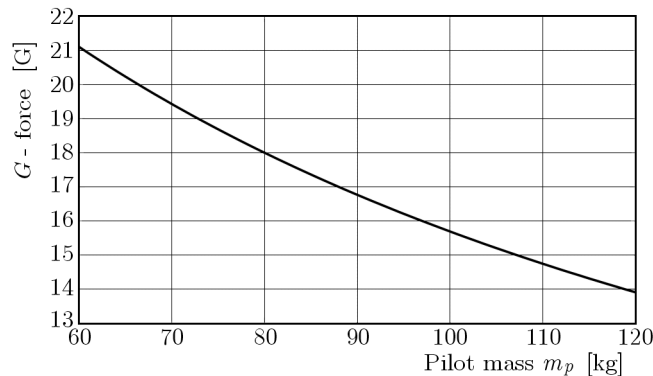

Fig. 5. Gravity load acting on the pilot during ejection

The speed of ejection seat in symmetrical motion is described with the following dependence

$$\mathbf{V}_f = \sqrt{\mathbf{V}_{xf}^2 + \mathbf{V}_{yf}^2} \tag{3.4}$$

where: $\mathbf{V}_{xf} = \mathbf{V}_f \cos\gamma_f$ and $\mathbf{V}_{yf} = \mathbf{V}_f \sin\gamma_f$ is the horizontal and vertical component of the seat speed, respectively, and γ_f is the inclination angle of the flight trajectory.

At the beginning, the initial speed of the ejection seat is to be determined in relation to the air at the moment when the cockpit guides are being left in function of the aircraft speed and the shot speed

$$\mathbf{V}_{f0} = \mathbf{V}_{f0}(\mathbf{V}_s, \mathbf{V}_0) \tag{3.5}$$

If the horizontal and vertical components of the speed are described as

$$\mathbf{V}_{xf0} = \mathbf{V}_{f0}\cos\gamma_f = \mathbf{V}_s - \mathbf{V}_0\sin\kappa_f \qquad \mathbf{V}_{yf0} = \mathbf{V}_{f0}\sin\gamma_f = \mathbf{V}_0\cos\kappa_f \tag{3.6}$$

The initial speed of the seat is

$$\mathbf{V}_{f0} = \sqrt{\mathbf{V}_{xf0}^2 + \mathbf{V}_{yf0}^2} = \sqrt{\mathbf{V}_s^2 + \mathbf{V}_0^2 - 2\mathbf{V}_s\mathbf{V}_0\sin\kappa_f} \qquad (3.7)$$

It is evident from (3.7) that the greater is the speed of the aircraft and the launch velocity, the greater is the initial speed of the seat. A pilot with a greater mass during ejection possesses a smaller speed of leaving the guides, hence the initial speed of the seat decreases while the pilot's mass increases with a constant speed of the aircraft.

The initial angle of the flight trajectory of the seat γ_{f0} is described with the following dependence

$$\gamma_{f0} = \arcsin\frac{\mathbf{V}_0\cos\kappa_f}{\mathbf{V}_{f0}} \qquad (3.8)$$

The initial angle of the trajectory of the seat in function of the speed is presented in Fig. 6. With an increase of the aircraft speed, the angle γ_{f0} decreases. A greater pilot's mass has an influence on a decrease of the launching speed $\mathbf{V}_0$ and a smaller value of γ_{f0} angle.
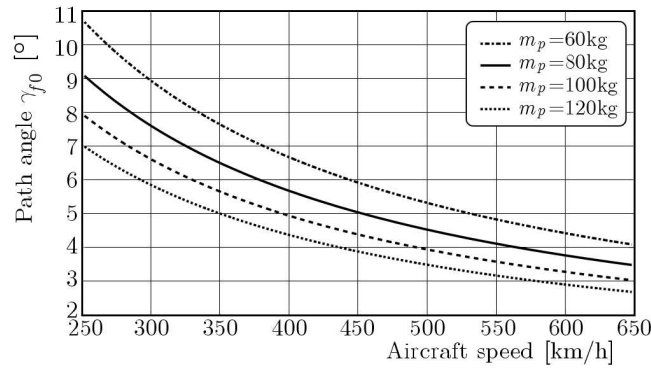

Fig. 6. Initial trajectory angle of the seat γ_{f0} in function of the aircraft speed

During ejection, the gravity force is acting on the seat. It is described with the following equation

$$\mathbf{F}_G = m\mathbf{g}(H) \qquad (3.9)$$

A drag force is acting on the moving seat which comes from inflowing air streams $\mathbf{F}_D$. The drag force vector possesses a sense that is opposite to the vector of the seat speed. The drag force depends on the area of the seat front cross-section, ejection height, drag coefficient and the speed of the seat in relation to the air. The data concerning masses and the dimensions of the seat were prepared on the basis of the authors' own research (Głowiński and Krzyżyński, 2011). The drag force is determined with the following dependence

$$\mathbf{F}_D = \frac{1}{2}\rho S C_D \mathbf{V}_f^2 \qquad \rho = \frac{p}{RT} \approx \rho_0\Big(1 + \frac{H}{44300}\Big)^{4.256} \qquad (3.10)$$

where ρ is the air density at altitude H [kg/m³] and ρ_0 is density of the sea level, S – cross--sectional area of the seat, C_D – drag coefficient.

The value of the drag force decreases with an increase of altitude, whereas it rises with an increase of speed. The load which the pilot is subject to from the inflowing streams of air (in the chest-back direction) in function of speed for various pilot's masses on altitude of the ejection of 250 m is presented in Fig. 7). With an increase of the pilot's mass, the load in the direction of the chest-back decreases. At the same time, an increase of the aircraft speed results in an increased gravity load.
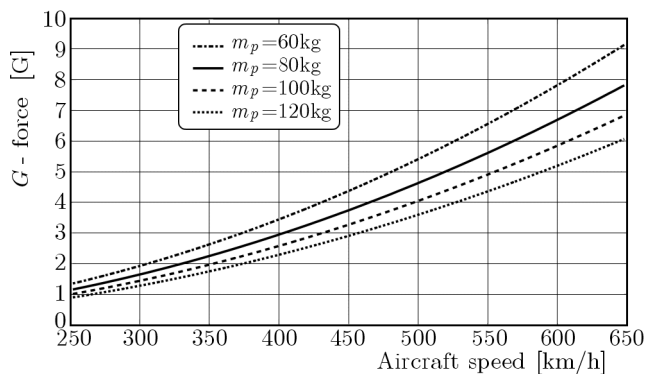
Fig. 7. Load from inflowing air streams acting on the seat in function of the aircraft speed

The air density and the drag force with which the air acts on the pilot during the flight of the seat decrease. The load from the inflowing streams of air (in the chest-back direction) in function of the ejection height for the speed of 650 km/h is presented in Fig. 8.
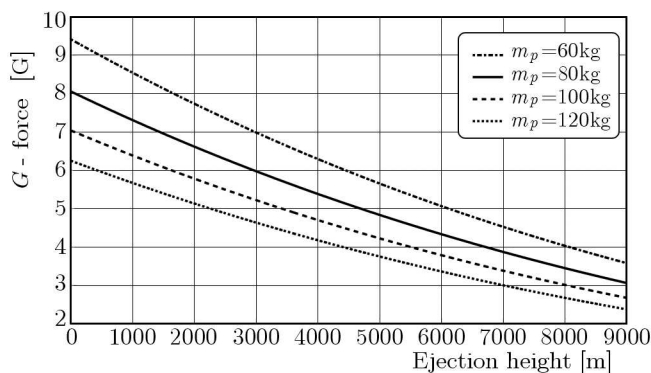

Fig. 8. Load from inflowing air streams acting on the seat in function of height

The equation of motion of the seat after ejection after a period of time $t \gg 0$ can be written as

$$F = m_f \mathbf{a}_f = m\mathbf{g} - \mathbf{F}_D = m\mathbf{g} - \frac{1}{2}\rho S C_D \mathbf{V}_f^2 \tag{3.11}$$

The maximum speed that is obtained by the seat over this period can be determined from the following dependence

$$\mathbf{V}_k = \sqrt{\frac{2m\mathbf{g}}{\rho S C_D}} \tag{3.12}$$

The velocity $\mathbf{V}_k$ depends on the pilot's mass and air density. The graph that presents the terminal velocity in function of the height is shown in Fig. 9.

Substitution of a positive constant $b = m\mathbf{g}/\mathbf{V}_k$ [kg/s] to equation (3.11) makes it possible to write this equation in the form

$$m\frac{d\mathbf{V}_f}{dt} = m\mathbf{g} - b\mathbf{V}_f \tag{3.13}$$

Equation of dynamics of the seat (3.13) can be resolved in the horizontal and vertical components

$$\frac{d\mathbf{V}_{xf}}{dt} = -\frac{b\mathbf{V}_{xf}}{m} = -\mathbf{g}\frac{\mathbf{V}_{xf}}{\mathbf{V}_k} \qquad \frac{d\mathbf{V}_{yf}}{dt} = -\mathbf{g} - \mathbf{g}\frac{\mathbf{V}_{yf}}{\mathbf{V}_k} = -\mathbf{g}\left(1 + \frac{\mathbf{V}_{yf}}{\mathbf{V}_k}\right) \tag{3.14}$$
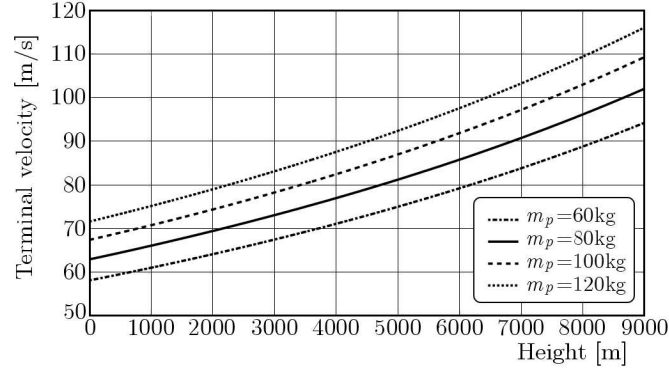
Fig. 9. Falling speed in function of height

After integration of relationships (3.14) within boundaries $(\mathbf{V}_{xf0}, \mathbf{V}_f)$, $(\mathbf{V}_{yf0}, \mathbf{V}_f)$ and substituting (3.6), the horizontal and vertical component of the vector of the seat speed are

$$\mathbf{V}_{xf} = (\mathbf{V}_s - \mathbf{V}_0 \sin \kappa_f) \exp\left(-\frac{\mathbf{g}}{\mathbf{V}_k} t\right)$$
$$\mathbf{V}_{yf} = \mathbf{V}_{f0} \cos \kappa_f \exp\left(-\frac{\mathbf{g}}{\mathbf{V}_k} t\right) - \mathbf{V}_k \left[1 - \exp\left(-\frac{\mathbf{g}}{\mathbf{V}_k} t\right)\right]$$
(3.15)

It is evident from equations (3.15) that if the falling time of the seat $t \gg \mathbf{V}_k/\mathbf{g}$, the seat is moving in compliance with the gravitational acceleration vector, which is compliant with real conditions.

After integration of dependence $(3.15)_1$ and transformations, the horizontal component of the path of the seat is

$$\mathbf{x} = \frac{(\mathbf{V}_s - \mathbf{V}_0 \sin \kappa_f)\mathbf{V}_k}{\mathbf{g}} \left[1 - \exp\left(-\frac{\mathbf{g}}{\mathbf{V}_k} t\right)\right]$$
(3.16)

If $t \ll \mathbf{V}_k/\mathbf{g}$, (3.16) is reduced to $\mathbf{x} = (\mathbf{V}_s - \mathbf{V}_0 \sin \kappa_f)t$, that is as if the seat was moving without taking into consideration the drag force from air streams. If $t \gg \mathbf{V}_k/\mathbf{g}$ then $\mathbf{x} = (\mathbf{V}_s - \mathbf{V}_0 \sin \kappa_f)\mathbf{V}_k/\mathbf{g}$ that is we obtain the range of the seat to attaining the shot height.

After integration of equation $(3.15)_2$ and after transformations, the vertical component of the path of the seat is

$$\mathbf{y} = \frac{\mathbf{V}_k}{\mathbf{g}}(\mathbf{V}_0 \cos \kappa_f + \mathbf{V}_k)\left[1 - \exp\left(-\frac{\mathbf{g}}{\mathbf{V}_k} t\right)\right] - \mathbf{V}_k t + H$$
(3.17)

Equation (3.17) is reduced to

$$\mathbf{y} = \begin{cases} \mathbf{V}_0 \cos \kappa_f t - \dfrac{\mathbf{g}}{2} t^2 & \text{for} \quad t \ll \dfrac{\mathbf{V}_k}{\mathbf{g}} \\[2mm] \dfrac{\mathbf{V}_k}{\mathbf{g}}(\mathbf{V}_0 \cos \kappa_f + \mathbf{V}_k) - \mathbf{V}_k t & \text{for} \quad t \gg \dfrac{\mathbf{V}_k}{\mathbf{g}} \end{cases}$$
(3.18)

that is the air drag force exerts a significant influence of the flight trajectory of the seat.

In order to determine the function $\mathbf{y} = \mathbf{y}(\mathbf{x})$, the time t is to be determined from equation (3.16)

$$\mathbf{x} = \frac{(\mathbf{V}_s - \mathbf{V}_0 \sin \kappa_f)\mathbf{V}_k}{\mathbf{g}} \left[1 - \exp\left(-\frac{\mathbf{g}}{\mathbf{V}_k} t\right)\right] \qquad \exp\left(-\frac{\mathbf{g}}{\mathbf{V}_k} t\right) = 1 - \frac{\mathbf{g}\mathbf{x}}{(\mathbf{V}_s - \mathbf{V}_0 \sin \kappa_f)\mathbf{V}_k}$$
(3.19)

$$t = -\frac{\mathbf{V}_k}{\mathbf{g}} \log\left(1 - \frac{\mathbf{g}\mathbf{x}}{(\mathbf{V}_s - \mathbf{V}_0 \sin \kappa_f)\mathbf{V}_k}\right)$$

After substituting (3.19) to dependence (3.17) and after simple transformations, the following is obtained

$$\mathbf{y} = \frac{\mathbf{x}(\mathbf{V}_0 \cos \kappa_f + \mathbf{V}_k)}{\mathbf{V}_s - \mathbf{V}_0 \sin \kappa_f} + \frac{\mathbf{V}_k^2}{\mathbf{g}} \log\left(1 - \frac{\mathbf{g}\mathbf{x}}{(\mathbf{V}_s - \mathbf{V}_0 \sin \kappa_f)\mathbf{V}_k}\right) + H \tag{3.20}$$

Equation (3.20) presents the flight height of the seat in function of the horizontal path covered by the seat. Hence, one may determine the height that the seat acquires after it has covered the component of the horizontal path $\mathbf{x}$.

4. Results

After implementation of the rearranged equations to the script that was created in the MATLAB program, the flight paths of the ejection seat were obtained depending on the pilot's mass. The diagrams in Figs. 10a,b present the flight path of the seat in relation to the aircraft in function of mass. The brightest shade presents the maximum height that is achieved by the seat. One can observe that with an increase of the pilot's mass, the maximum height obtained by the seat for a given distance decreases. The simulations were conducted for the aircraft velocity $V_s = 250\,\text{km/h}$ and $V_s = 650\,\text{km/h}$. The ejection height is $H = 250\,\text{m}$. The simulation time was set to $1.5\,\text{s}$, i.e. until the moment when the AD-3 timer release unit that releases the seatbelt lock begins to operate. With a greater speed, it takes a shorter time for the pilot to fly over the aircraft stabilizer, which makes it possible for him to open the seatbelts sooner through manual doubling of the operation of the AD-3 timer release.
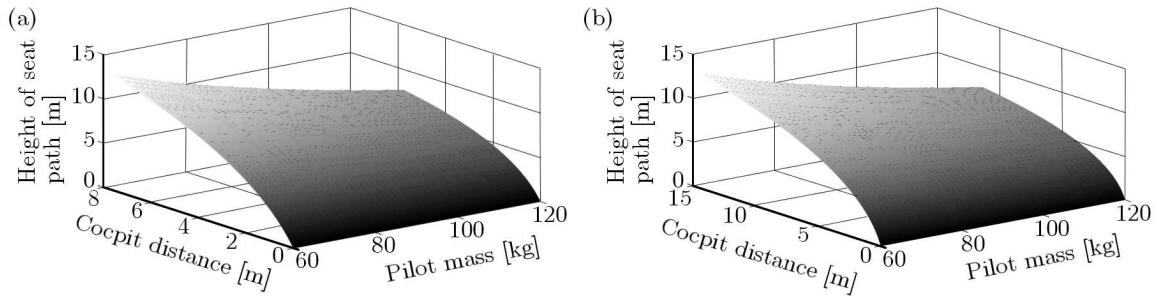

Fig. 10. Flight path of the seat in relation to the aircraft; (a) $\mathbf{V}_s = 250\,\text{km/h}$, (b) $\mathbf{V}_s = 650\,\text{km/h}$

The most interesting issue is the smallest distance to the upper part of the vertical stabilizer of the aircraft that is possessed by the seat during flight (assuming that the height of the seat is $l_f = 1.2\,\text{m}$). For this purpose, the following dependence is used

$$\begin{aligned}
\mathbf{d}_I &= \sqrt{\left(L_I - \mathbf{V}_s t - \frac{1}{2}l_f\right)^2 + \left(h_2 - \mathbf{y} - H - \frac{1}{2}l_f\right)^2} \\
\mathbf{d}_{II} &= \sqrt{\left(L_{II} - \mathbf{V}_s t - \frac{1}{2}l_f\right)^2 + \left(h_2 - \mathbf{y} - H - \frac{1}{2}l_f\right)^2}
\end{aligned} \tag{4.1}$$

Figure 11 presents the distance from the vertical stabilizer in function of the pilot's mass and the distance from the seat guides in cockpit II in the aircraft including the characteristic points marked that describe the smallest distance from the stabilizer. The simulation time is $0.8\,\text{s}$, which ensures that the area of the vertical stabilizer is reached by the seat. An increase of the pilot's mass results in a decrease of the minimum distance between the seat and the stabilizer. In the case of a greater mass, this distance is reached in a larger horizontal distance from the seat guides than in the case of a small pilot's mass.
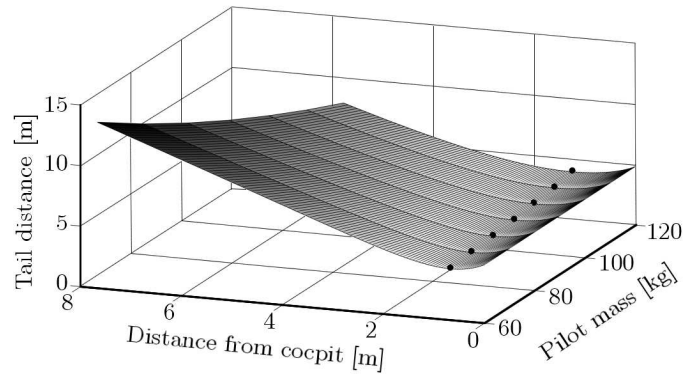
Fig. 11. Distance from the vertical stabilizer in function of the pilot's mass, $\mathbf{V}_s = 250\,\mathrm{km/h}$

Figure 12a presents the influence of the pilot's mass and the speed of the aircraft on the minimum distance from the stabilizer. An increase of the pilot's mass from 60 kg to 120 kg with the speed of 250 km/h reduces the minimum distance by ca. 7%, whereas the same increase of the mass for the maximum speed of 650 km/h decreases the minimum distance from the tail of the aircraft by ca. 22%. The smallest distance to the stabilizer (the darkest area in the figure) corresponds to the pilot's mass of 120 kg and the aircraft speed of 650 km/h.
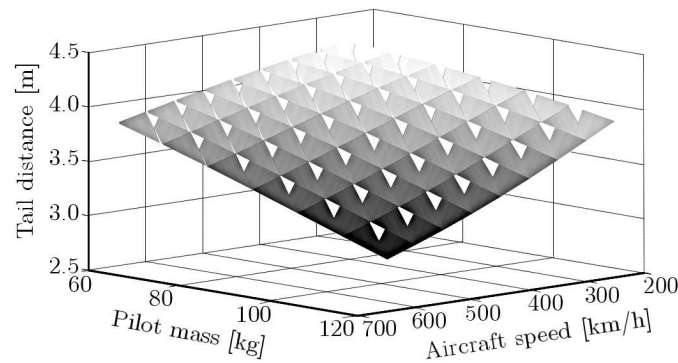

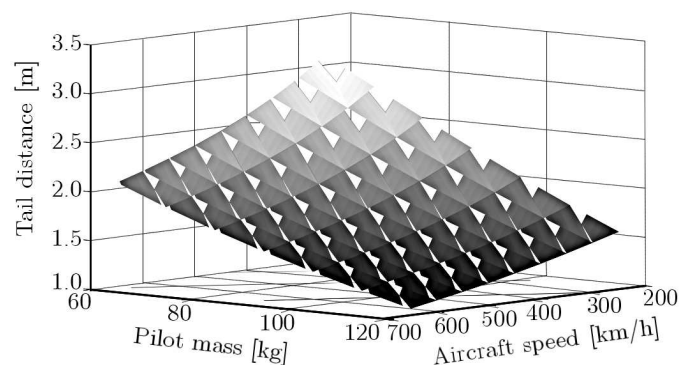Fig. 12. Distance from the vertical stabilizer depending on the pilot's mass and speed of the aircraft

Fig. 13. Distance from the vertical stabilizer depending from the pilot's mass and the speed of the aircraft, $\mathbf{V}_0 = 10\,\mathrm{m/s}$

Trained pilots of jet aircrafts do ejection trainings with the use of the Ground Ejection Training Device called UTKZ. A real ejection seat is used for ejection, while the pyrocartridge possesses a reduced quantity of the powder charge. A reduction of the force of the pyrocartridge lessens the probability of the spine being damaged during the ejection. A simulation was con-

ducted concerning ejection with the use of this type of pyrocartridge ($\mathbf{V}_0 = 10\,\mathrm{m/s}$). Figure 13 presents the results that were obtained. One can observe that in the case of a mistaken use of the pyrocartridge with a reduced charge in relation to the real aircraft, there is a risk of the pilot's collision with the vertical stabilizer during an emergency on the flight.

5.   Conclusions

This paper summarizes the ejection process simulation of an ejection seat using an analytical method. The simulation results have been shown in detail to analyse the ejection performance at adverse the attitude. The mathematical model of ejection describing motion of the seat and the loads acting on the pilot with the respect to height of the flight, weight of the seat and speed of the aircraft makes it possible to conduct simulations and to obtain data concerning the flight path and its inclination angle depending on height (which is important when the fall of the seat down to the ground is analyzed). The results obtained can be successfully used for an analysis of the ejection process during investigations concerning air accidents, and they are compliant with Maryniak *et al.* (2005), [7] and Yu *et al.* (2010). An introduction of any data to the script (the aircraft speed, the gravity load during an ejection, the dimensions of the aircraft) allow one to obtain information concerning the range of the flight of the seat. When possessing data concerning the location of the fall of the seat and a reading from the recorder (the height and speed of the aircraft during the ejection process), one may determine the location of leaving the aircraft. In further research, it is advisable to analyze ejection in an ascending and descending flight as well as when the aircraft is banked and with the occurrence of gravity load. There are some limitations of the present work, for example the model does not take into account the reaction of the aircraft to the launching of the ejection seat; it was assumed that after the ejection process, the aircraft is moving in a rectilinear and uniform flight. In reality, there occurs a pitching moment (the force of pyrocartridge reaction) and a reduction of mass of the aircraft, which should be perfected in the future to improve the calculation precision. Those analysis, however, will be covered by further investigations.

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