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# Subjective Factors in Flight Safety

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## 1. Introduction

The central deterministic element of the aircraft conventional control systems is the pilot – operator. Such systems are called as active endogenous subjective systems, because (i) the actively used control inputs (ii) origin from inside elements (pilots) of the system as (iii) results of operators' subjective decisions. The decisions depend on situation awareness, knowledge, practice and skills of pilot-operators. They may make decisions in situations characterized by a lack of information, human robust behaviors and their individual possibilities. These attributes as subjective factors have direct influences on the system characteristics, system quality and safety.

Aircraft control containing human operator in loop can be characterized by subjective analysis and vehicle motion models. The general model of solving the control problems includes the passive (information, energy - like vehicle control system in its physical form) and active (physical, intellectual, psychophysiology, etc. behaviors of subjects - operators) resources. The decision-making is the appropriate selection of the required results leading to the best (effective, safety, etc.) solutions.

This chapter defines the flight safety and investigates aircraft stochastic motion. It shows the disadvantages of the stochastic approximation and discusses, how, the methods of subjective analysis can be applied for the evaluation of flight safety.

The applicability of the developed method of investigation will be demonstrated by analysis of the aircraft controlled landing. The applied equation of motions describes the motion of aircraft in vertical plane, only. The boundary constraints are defined for velocity, trajectory angle and altitude. The subjective factor is the ratio of required and available time to decision on the go-around. The decision depends on the available information and psycho-physiological condition of operator pilots and can be determined by the theory of statistical hypotheses. The endogenous dynamics of the given active system is modeled by a modified Lorenz attractor.

## 2. Flight safety

### 2.1 Definitions

Safety is the condition of being safe; freedom from danger, risk, or injury. From the technical point of view, safety is a set of methods, rules, technologies applied to avoid the emergency situation caused by unwanted system uncertainties, errors or failures appearing randomly.

Safety and security are the twin brothers. The difference between them could be defined such as follows:

- *Safety:* avoid emergency situation caused by unwanted system uncertainties, errors or failures appearing randomly.
- *Security:* avoid emergency situations caused by unlawful acts (of unauthorized persons) – threats.

Safety related investigations start as early as the development of the given system. At the definition and preliminary phase of a new system, one should also concentrate some efforts on the (i) potential safety problems, (ii) critical situations, (iii) critical system failures, (iv) and their possible classification, identification. After the risk assessment, the next step is the development of a set of policies and strategies to mitigate those risks. Generally, the safety policies and strategies are based on the synergy of the

- physical safety (characteristics of the applied materials, structural solutions, system architecture that help to overcome safety critical – emergency situations),
- technical safety (dedicated active or passive safety systems including e.g. sensors to enhance situation awareness),
- non-technical safety (such as policy manuals, traffic rules, awareness and mitigation programs).

The safety of any systems can be evaluated by using the risk analysis methods. Risk is the probability that an emergency situation occurs in the future, and which could also be avoided or mitigated, rather than present problems that must be immediately addressed.

### 2.2 Flight safety metrics

The evaluation of the flight safety is not a simple task. There is no uniformly applicable metrics for the evaluation. Some governments have already published (CASA, 2005; FAA, 2006; Transport, 2007) their opinion and possible methodologies for flight safety measures that are applied by evaluators (Ropp & Dillmann, 2008). The problem is associated with the very complex character of flight safety depending on the developed and applied

- safety plan with management commitment,
- documentation management,
- risk monitoring,
- education and training,
- safety assurance (quality management on safety),
- emergency response plan.

Risk analyses methods defining the probability of emergency situations or risks are very widely used for flight safety evaluation. Metrics of risk is the probability of the given risk as an unwanted danger event. This probability has at least four slightly different interpretations:

- classic - the unwanted event,
- logic - the necessary evil,
- objective - relative frequency,
- subjective - individual explanation of the events.

In practice, the analysis of accident statistics could characterize the flight risks. Such statistics give the evidences for the well-known facts (Rohacs, 1995, 2000; Statistical 2008): (i) the longest part of the flight (with about 50 - 80 % of flight time) is the cruise phase, which only accounts for 5 - 8 % of the total accidents and 6 - 10 % of the total fatal accidents, (ii) the most dangerous phases of flight are the take-off and landing, because during this about 2 % of flight time the 25 - 28 % of fatal accidents are occurring, and (iii) generally nearly 80 % of the accidents are caused by human factors and about 50 % of them are initiated by the pilots.

A good example of using accident statistics is shown in Figure 1. Beside showing the effects of technological development on the reduction of flight risks, it also shows that since 2003, the European fatal accident rate - as fatalities per 10 million flights - has increased, without knowing – so far – the reason causing it.


Fig. 1. Characterization of the European accident statistics (EASA, 2008).

The accident statistics could be also used for flight safety analysis in original, or unusual method. While accident statistics demonstrate a considerable higher risk, accident rates for small aircraft, according to the Figure 2., the ratio of all and fatal accidents are nearly the same for airlines and general aviation. This means that the small and larger civilian aircraft are developed, designed, and produced with the same philosophy, at least the same safety approach and 'structural damping of damage processes'. The flight performances, flight dynamics, load conditions, structural solutions are different for small and larger aircraft, and therefore the accidents rates are also different. However, the risk of hard aftermath, appearing the fatal accident following the accidents are the same.

### 2.3 Human factors

In 1908, 80 % of licensed pilots were killed in flight accident (Flight, 2000). Since that, the World and the aviation have changed a lot. After 1945, the role of technical factors in causing the accidents (and generally in safe piloting) is continuously decreasing while the role of human factors is increasing.

As it was outlined already, nearly 80 % of accidents are caused by human factors. (Rohacs, 1995, 2000; Statistical, 2008). While, only 4 -7 % of accidents are defined by the "independent investigators" as accident caused by unknown factors. According to Ponomerenko (2000) this figure might be changed when one tries to establish the truth in fatal accidents,

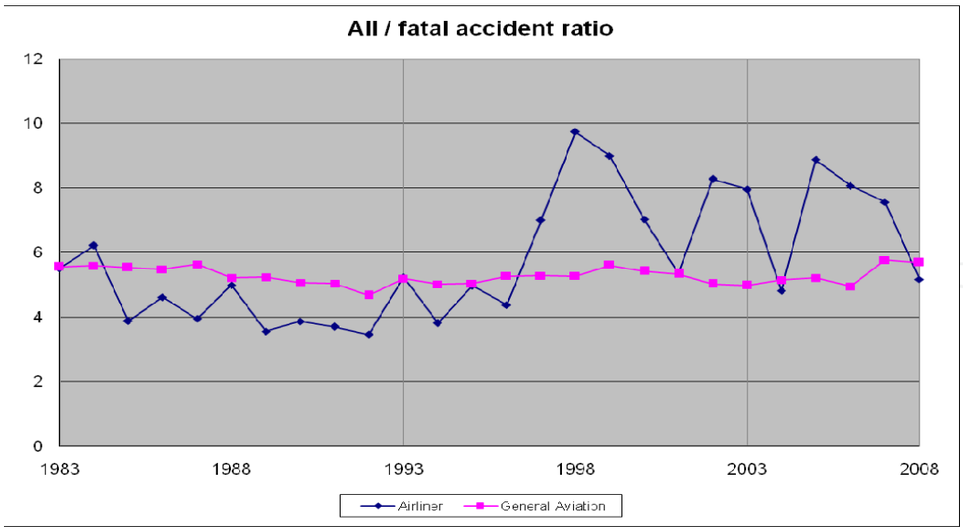


Fig. 2. An original way to compare airliner and GA accident statistics.

especially by taking into account the socio-psychological aspects and use of " 'guilt' and 'guilty' as the 'master key' to unlock the true cause of the accident. Hence, the bias of the investigators often does not represent the interest of the victims, but that of the administrative superstructure. It side steps the legal and socio-psychological estimation of aircrew behavior, and replaces it by formal logic analysis of known rules: permitted/forbidden, man or machine, chance/relationship, violated/not violated, etc."

Accident investigations show that human factors could be divided into three groups depending on their origins.

- Technical factors: disharmony in human - machine interface. Most known cases from this group are called as PIDs (pilot induced oscillations). Some of these factors, like limitations of the control stick forces are included even into the airworthiness requirements.
- Ergonomic factors: a lack of ergonomic information display, guidance control, out-of-cockpit visibility, design of instrument panel, as well as of adequate training [Ponomarenko 2000].
- Subjective factors: un-predictable and non-uniform man's behavior. Making wrong decisions because the lack of knowledge and practice of operators.

The different groups have nearly the same role in accident casualty, equal to 25, 35, 40 %, respectively. Others (Lee, 2003) call the same type of factors as system data problems, human limitation and time related problems.

The first group of human factors, harmonization of the man-machine interface from the technical side of view is well investigated and such type of human factors are taken into account in aircraft development and design processes. Generally, the handling quality or (nowadays) the car free characteristics are the merits and used as main philosophical approaches to solve these types of problems.

The ergonomic factors have been investigated a lot for last 40 - 50 years. The third generation of the fighters had been developed with the use of ergonomics, especially in

development of the cockpit, that were radically redesigned for that period. However, the ergonomic investigations had used the governing idea, how to make better for operator. A new approach has developed for last 20 years that investigates the 'ergatic' systems (see for example Pavlov & Chepijenko, 2009) in which the operator (pilot) one of the important (might be most important) element of the systems, and the psycho-physiological behaviors of the operator may play determining roles in operation of system.

The third group of human factors has not investigated on the required level yet. Generally, the key element of human reaction on the situation, especially on the emergency situation is the time. *However, the speed and time of reaction is "... not determined by the amount of processed information, but by the choice of the signal's importance, which is always subjective and affected by individual personality traits" (Ponomarenko 2000).* In an emergency situation, flight safety does not depend as much on the detailed information on the emergency situation and the size of pilot supporting information, as on the whole picture including space and time, knowledge and practice of pilots and the actual determination of the ethical limits of man's struggle with the arisen situation.

Flight safety could also be analyzed with the prediction of the future air transport characteristics. For example, the NASA initiated zero accident project, (Commercial, 2000; Shin, 2000; White, 2009) leads to the following general conclusion: before introducing the wide-body aircraft, the risk of flight was decreased by a factor of 10, but this cannot be further reduced with the present technical and technological methods (Rohacs, 1998; Shin, 2000). Even so, the number of aircraft and the number of yearly, daily flights are continuously increasing (Fig. 3.); Seeing this, the absolute number of accidents is expected to increase in the future, which might even lead to the vision made by Boeing, in which by 2016/17, each week one large-body aircraft is envisioned to have an accident. "Given the very visible, damaging, and tragic effects of even a single major accident, this number of accidents would clearly have an unacceptable impact upon the public's confidence in the aviation system and impede the anticipated growth of the commercial air-travel market" (Shin, 2000). Therefore, new methods like emergency management might need to be developed and applied to keep the absolute number of accidents on the present level.

Seeing the envisioned rapid development of the future aviation, especially the small aircraft transportation system, the conclusion derived from the zero accident program and use of the subjective analysis in flight safety investigation might be relevant to be kept in mind.

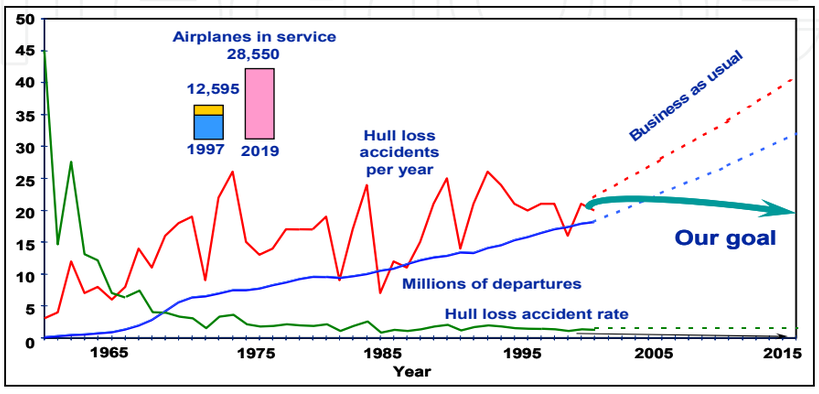


Fig. 3. The NASA zero accident program (Commercial, 2000).

## 3. Flight safety evaluation

### 3.1 Technical approach to flight safety evaluation

Technically, flight risks are always initiated by the deviations in the system parameters. Therefore, the investigation of the system parameter uncertainties and anomalies might be applied as a basis to evaluate flight safety. Flight safety is the risk that an emergency situation occurs, when the system parameters (at least one of them) are out of the tolerance zones. In the view of this, flight safety might be characterized by the probability of the deviations (in the structural and operational characteristics) being larger than those predetermined by the airworthiness (safety) requirements (Bezapasnostj 1988, Rohacs & Németh, 1997).

Mathematically, flight operation quality, $\mathbf{Q}_r(t)$, could be given in the following simple form:

$$\mathbf{Q} \equiv \{a_i\} \quad , \quad i = 1,\mathrm{n} \tag{1}$$

where $a_i$ are the parameters defining the attributes of the given aircraft or system. In a more general form, it could be given as:

$$a_i = f\left(a_1, a_2, \ldots a_{i-1}, a_{i+1}, \ldots a_n\right) . \tag{2}$$

In real flight situations, the real quality of operation $\mathbf{Q}_r(t)$ is deviated from the design (nominal) quality $\mathbf{Q}_r^n(t)$:

$$\delta\, \mathbf{Q}_{\mathrm{r}}(t) = \mathbf{Q}_{\mathrm{r}}(t) - \mathbf{Q}_{\mathrm{r}}^{\mathrm{n}}(t) \quad . \tag{3}$$

For each case, the acceptable level of deviation is maximized by the flight safety threshold ($\delta_{\mathrm{fs}}$),

$$\left|\delta\, \mathbf{Q}_{\mathrm{r}}(t)\right| \geq \delta_{\mathrm{fs}} \quad , \tag{4}$$

where $P\left(\left|\delta\, \mathbf{Q}_{\mathrm{r}}(t)\right| \geq \delta_{\mathrm{fs}}\right)$ describes the probability of a flight event (flight out of prescribed operational modes).

By summing all the potential flight events, flight safety ($P_{fs}$) could be given with the following probability:

$$P_{\mathrm{fs}} = 1 - \sum_{i=1}^{n} R_i(t)\, P_i(t) \tag{5}$$

where $R_i(t)$ - is the risk of flight accident.

For time period [0, T] the following integral risk can be applied:

$$\tilde{P}_{\mathrm{fs}} = 1 - \frac{1}{\mathrm{T}} \int_0^{\mathrm{T}} \left(1\text{-}P_{\mathrm{fs}}(t)\right) dt \quad . \tag{6}$$

Because $\delta \mathbf{Q}_r(t)$ is the random value with probability density, $\rho(\delta \mathbf{Q}_r(t))$, the flight safety level can be given as:

$$P_{\text{fs}} \equiv P\left(\left|\delta \mathbf{Q}_r(t)\right| \le \delta_{\text{fs}}\right) = \int_{-\delta_{\text{fs}}}^{\delta_{\text{fs}}} \rho\left(\delta \mathbf{Q}_r\right) d\delta \mathbf{Q}_r \quad . \tag{7}$$

According to the Tchebyshev inequality

$$P\left(\left|\delta \mathbf{Q}_r(t)\right| \succ \delta_{\text{fs}}\right) \le D\left(\delta \mathbf{Q}_r\right) / \delta_{\text{fs}}^2 \tag{8}$$

the flight safety level takes the form:

$$P_{\text{fs}} \equiv P\left(\left|\delta \mathbf{Q}_r(t)\right| \le \delta_{\text{fs}}\right) \ge 1 - D\left(\delta \mathbf{Q}_r\right) / \delta_{\text{fs}}^2 \quad , \tag{9}$$

where $D(\delta \mathbf{Q}_r)$ is the dispersion of $\delta \mathbf{Q}_r$ .

Such type of system approach was developed, applied and improved. Generally, once the aircraft is investigated as a dynamic system, the effects of the system anomalies could be given by the following type of probabilities (Rohacs 1986; Rohacs & Nemeth, 1997):

$$P_1\left\{ \mathbf{y}(t)\Big|_{t_0 \le t \le t+\tau,\ \mathbf{x}\in\Omega_{\text{x}},\ \mathbf{u}\in\Omega_{\text{u}},\ \mathbf{z}\in\Omega_{\text{z}},\ \mathbf{p}\in\Omega_{\text{p}}} \right\} , \tag{10.a}$$

$$P_2\left\{ \mathbf{u}(t)\Big|_{t_0 \le t \le t+\tau,\ \mathbf{x}\in\Omega_{\text{x}},\ \mathbf{y}\in\Omega_{\text{y}},\ \mathbf{z}\in\Omega_{\text{z}},\ \mathbf{p}\in\Omega_{\text{p}}} \right\} , \tag{10.b}$$

where $\mathbf{y} \in R_r$ defines the output (measurable) signal vector (measured vector of operational characteristics) $\mathbf{x} \in R_n$ is the state vector, $\mathbf{u} \in R_m$ gives the input (control) vector, $\mathbf{z} \in R_i$ stands for the vector of environmental characteristics (vector of service conditions), $\mathbf{p} \in R_k$ is the parameter vector characterizing the state of the aircraft, $t$ defines the time, $\tau$ provides the elementary time, $\Omega_{\text{x}}$, $\Omega_{\text{y}}$, $\Omega_{\text{z}}$, $\Omega_{\text{u}}$, $\Omega_{\text{p}}$ are the allowed ranges for the given characteristics.

If the joint density function,

$$f_{\Sigma} = f\left[\mathbf{x}(\text{t}), \mathbf{u}(\text{t}), \mathbf{z}(\text{t}), \mathbf{p}(\text{t}), \mathbf{y}(\text{t})\right] \tag{11}$$

is known, then the recommended characteristics can be calculated as:

$$\text{P}_1\left\{\mathbf{y}(\text{t}) \in \mathbf{\Omega}_{\text{y}} \middle| \ldots\right\} = \frac{\int_{\Omega_i} f_{\Sigma} \text{d}\mathbf{x}\text{d}\mathbf{u}\text{d}\mathbf{z}\text{d}\mathbf{p}\text{d}\mathbf{y}}{\int_{-\infty}^{+\infty} \text{d}\mathbf{y} \int_{\Omega_j} f_{\Sigma} \text{d}\mathbf{x}\text{d}\mathbf{u}\text{d}\mathbf{z}\text{d}\mathbf{p}} \quad \begin{matrix} (i \in \mathbf{x},\mathbf{u},\mathbf{z},\mathbf{p},\mathbf{y}) \\ (j \in \mathbf{x},\mathbf{u},\mathbf{z},\mathbf{p}) \end{matrix} , \tag{12.a}$$

$$\text{P}_2\left\{\mathbf{u}(\text{t}) \in \mathbf{\Omega}_{\text{u}} \middle| \ldots\right\}. = \frac{\int_{\Omega_i} f_{\Sigma} \text{d}\mathbf{x}\text{d}\mathbf{u}\text{d}\mathbf{z}\text{d}\mathbf{p}\text{d}\mathbf{y}}{\int_{-\infty}^{+\infty} \text{d}\mathbf{u} \int_{\Omega_j} f_{\Sigma} \text{d}\mathbf{x}\text{d}\mathbf{z}\text{d}\mathbf{p}\text{d}\mathbf{y}} \quad \begin{matrix} (i \in \mathbf{x},\mathbf{u},\mathbf{z},\mathbf{p},\mathbf{y}) \\ (j \in \mathbf{x},\mathbf{z},\mathbf{p},\mathbf{y}) \end{matrix} . \tag{12.b}$$

Unfortunately, this method of determining the effects of the system anomalies on the flight safety is often considered to be too complex, while it is found to be reasonable, since the formulas given above could be supported with statistical data collected during aircraft operation. The method of determining the flight risk on the probability approach (as given in (Gudkov & Lesakov, 1968; Howard, 1980)) is envisioned to be too complicated, once it is also desirable to consider the so-called common (failures appearing at the same time due to different reasons) and depending failures or errors. The Figures 4 and 5 show a nice example of using the described method is the investigation changes in geometrical and operational characteristics of aircraft investigated by (Rohacs 1986) and published in several articles, like (Rohacs, 1990).

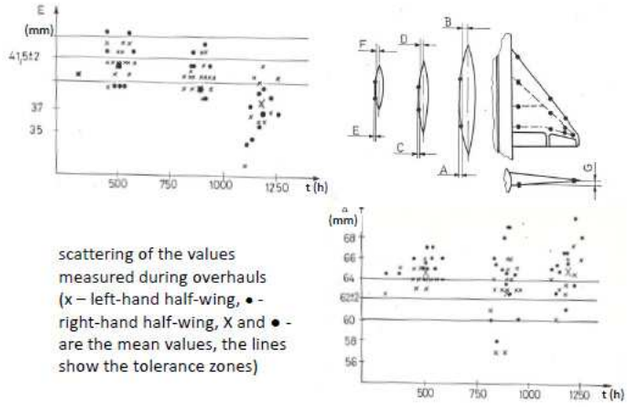


Fig. 4. The level book and examples of the measuring data for Mig-21.

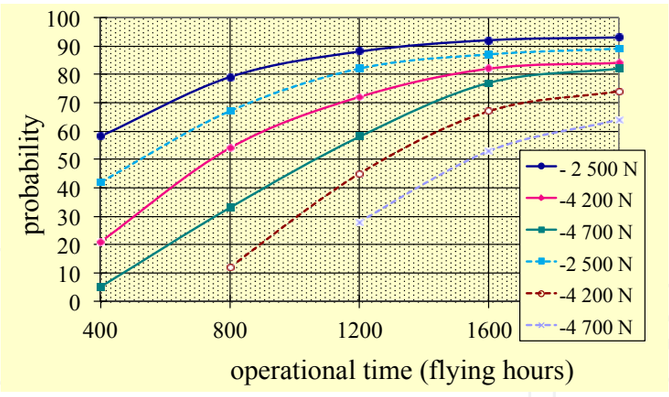


Fig. 5. Probability of lack of generated lift at fighters Míg-21 due the changes in wing geometry during the operation (line - single seat, dot line - double seats aircraft)

### 3.2 Stochastic model of flight risk

The aircraft's motion is the result of the deterministic control and the stochastic disturbance processes. Such motion might be mathematically given by the following stochastic (random) differential equation, called as diffusion process (Gardiner, 2004):

$$\dot{x} = f(x,t) + \sigma(x,t)\eta(t) \ , \tag{13}$$

Naturally, this equation might be also given in vector form. The first part of the right side of the equation describes the drift (direction of the changes) of the stochastic process passing through $x(t) = X$ at the moment $t$, while the second part shows the scattering (variance) of the random process. Here $\eta(t)$ is the random disturbance (e.g. air turbulence, or cumulative effects of random load processes, including even extreme loads as hard touchdown, etc.).

Seeing that the future states depend only on the present sate, the equation (13) is in fact a Markov process (Ibe, 2008; Rohacs & Simon, 1989; Tihonov, 1977). Such process can be fully described by its transition probability density function:

$$p(x_2, t_2 | X_1, t_1), \qquad (t_2 > t_1) \quad , \tag{14}$$

which characterizes the distribution probability of the continuous random process ($x(t)$) at the moment $t_2$, once it's passing through the $x(t) = X$ at time $t_1$.

The transition probability density function can be described by the following Fokker - Planck - Kolmogorov equations (Gardiner, 2004):

$$\frac{\partial p(x_2,\ t_2 | X_1,\ t_1)}{\partial t_2} = -\frac{\partial}{\partial x_2}\left[ f(x_2,\ t_2)\, p(x_2,\ t_2 | X_1,\ t_1) \right] +$$

$$+\frac{1}{2}\frac{\partial^2}{\partial x_2^2}\left[ \sigma^2(x_2,\ t_2)\, p(x_2,\ t_2 | X_1,\ t_1) \right] , \tag{15.a}$$

or

$$\frac{\partial(x,\ t)}{\partial t} = -\frac{\partial}{\partial x}\left[ f(x,\ t)\, p(x,\ t) \right] + \frac{1}{2}\frac{\partial^2}{\partial x^2}\left[ \sigma^2(x,\ t)\, p(x,\ t) \right]. \tag{15.b}$$

Statistic flight mechanics has already worked out several methods for the application of such models. For example, the statistical linearization through the proof of the sensitivity function matrix to the flight mechanic models and generating out the set of equations for the moments of the investigated stochastic process could be used to study the scattering of the process.

Using the equations (15.a), (15.b), which define the Markov process, the following definition could be made:

$$p(X_2,\ t_2 | X_1,\ t_1) = \sum_{X(t)} p(X_2,\ t_2 | x,\ t)\, p(x,\ t | X_1,\ t_1), \qquad (t_2 \geq t \geq t_1) \quad , \tag{16}$$

This is called Chapman - Kolmogorov – Smoluchovski equation. It gives the possibility to approximate the investigated non-linear stochastic process with continuous time and state space with a Markov chain with continuous time and discrete state space. This leads us back to the situation chain process.

The space of the motion variables can be divided into several subspaces, called as situations. The motion of the aircraft is in fact a time invariant series of situations. This is the situation dynamics.

Accidents are the results of the situation process, which is assumed to be similar to the one given in the Figure 6. Here, *N* marks the normal, conventional flight, $S_1$, $S_2$, $S_3$ are different states related to the case when the aircraft has one (*F1)*, two (*F2*), or three serious system failures ($F_3$), while *A* shows the accident situation (Rohacs & Nemeth, 1997; Rohacs, 2000).

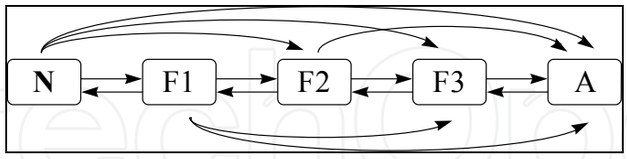


Fig. 6. Simple graph model of aircraft pre-accident process

The Markov chain can be described by the transition probabilities, $\beta_{i,j}$. These variables give the probability of moving the aircraft from a state (situation) $S_i$ to a state $S_j$. As it is known, this type of process can be approximated by Markov process, under the following conditions:

- the transition from one state into another occurs in a significantly short time,
- the probability of a transfer from one state into another through one or more other states is a limited, and
- the time spent in the states could be approximated by an exponential distribution.

Under the conditions mentioned above, the process could be described with the following model:

$$\dot{\mathbf{P}}(t) = \mathbf{P}_t(t)\mathbf{P}(t) \ , \tag{17}$$

where **P**(t)=[Pi(t)] is a vector of probabilities defining the states $S_i$ (*i*=*N*, *F1*, *F2*, *F3*, *A*).

At this stage, one should give the applicable graph model and estimate the transition probability matrix.

In this simple case, the aircraft's operational process – as a stochastic process with continuous time and discrete states shown in the Fig. 6. – could be approximated by the following Markov model:

$$\dot{\mathbf{P}}(t) = \boldsymbol{\beta}(t)\mathbf{P}(t) \tag{18}$$

where **P**(t)=[P i(t)] is a vector of probabilities that the aircraft is in the states $S_i$ (*i*=*N*, *F1*, *F2*, $F_3$, *A*), and

$$\boldsymbol{\beta}(t)=[\beta\ i,j] \tag{19}$$

is a time depending transition matrix:

$$\boldsymbol{\beta}(t)=\begin{bmatrix} -\beta_{N,F1}-\beta_{N,F2}-\beta_{N,F3}-\beta_{N,A} & -\beta_{F1,N} & 0 & 0 & 0 \\ \beta_{N,F1} & -\beta_{F1,N}-\beta_{F1,F2}-\beta_{F1,F3}-\beta_{F1,A} & -\beta_{F2,F3} & 0 & 0 \\ \beta_{N,F2} & \beta_{F1,F2} & -\beta_{F2,F1}-\beta_{F2,F3}-\beta_{F2,A} & -\beta_{F3,F2} & 0 \\ \beta_{N,F3} & \beta_{F1,F3} & \beta_{F2,F3} & -\beta_{F3,F2}-\beta_{F2,A} & -\beta_{A,F3} \\ \beta_{N,A} & \beta_{F1,A} & \beta_{F2,A} & \beta_{F3,A} & -\beta_{A,F3} \end{bmatrix}$$

Our theoretical and practical investigations on flight safety showed that the aircraft's operational process is a complicated process. For example, if a pilot reports an in-operating engine, than ATCOs are often to make 40 - 100 times more mistakes relative to normal circumstances. The simplified graph model of flight situations - taking into account such effects - is given in the Figure 7. The advantage of this representation method over the others, could be summarized in the followings. Firstly, this model includes a new state, called state of anomalies (*An*), in which the aircraft does not have any failures or errors, but still, its characteristics are essentially deviating from their nominal values. Secondly, the total amount of states are decomposed or grouped into four subparts (structure, pilot, air traffic control, surroundings).

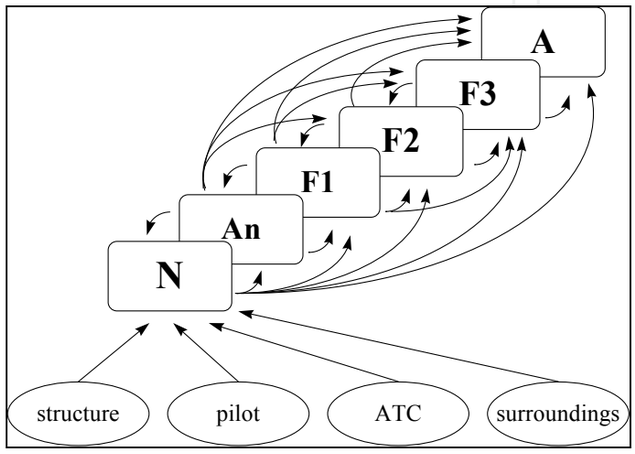


Fig. 7. The suggested general graph model of aircraft.

To simplify the representation of this method, the Figure 7. shows only the nominal state decomposition (Rohacs & Nemeth, 1997; Rohacs, 2000). Even so, the different numbers of failures are further decomposed. States *N* is a prescribed nominal state. States *An* and *F1* might only be initiated by the anomalies or failures in one of the aircraft's flight operation subsystems (e.g. aircraft structure, pilot, ATC, surroundings). On the other hand, the states *F2*, *F3* might be initiated by two or three failures appearing in any combination of the subsystems. For example *F2* may contain mistake of the pilot and ATCO, or two aircraft structural (system) failures.

According to these specific features of the model, the general Markov model should have 43 states. For example in our model, the state number 21, is the state with two failures generated in the structure and one is initiated by the mistake of the pilot. As a consequence, the transfer matrix is composed of 43 x 43 elements, while the elements of the matrix are the linear functions of **P**(t):

$$\beta i,j = \beta i,j,o + \mathbf{K}i,j\ \mathbf{P}(t)\ ; \tag{20}$$

where, $\beta i,j,o$ is the initial transfer matrix element, **K**i,j is the vector of coefficients. The vector **K**i,j may contain zero elements, too, if the given state has no influence on transfer process.

The determination of the vector elements **K**i,j, is based on the theory of anomalies, dealing with the calculation of the real deviations, characteristics, and distributions. For example,

human error depends on weather, traffic situations, or possible system failures. Naturally, if the aircraft is piloted by pilot with limited skills, then the coefficients would be higher than it is for the conventional small aircraft operations. After the evaluation of different models based on the above discussed Markov and semi-Markov processes, we found that the inadequate initial data and the relatively large number of states makes the semi-Markov process irrelevant for our purposes.

Due to the large number of states, the developed model might be seen too complex. On the other hand, by the analysis of the potential methods to simplify the model, it was found that the suggested approach can be transferred to the model shown in the Figure 7. This is reasonable, since from a flight safety point of view, the most important is the transfer of one state into another, and not the detail how that transfer could be made. Therefore, the transition matrix element, $\beta_{F1}$, $\beta_{F2}$, describing the transfer from one failure state (*F1*) into the state with two failures (*F2*) can be given in the following form:

$$\beta_{F1,F2} = \frac{\sum_{i,j} \beta_{F1_i,F2_j} P_{F1_i}}{\sum_{k,i} \beta_{An_k,F1_i} P_{An_k}} \ , \tag{21}$$

where *An* indicates the state with anomalies, and *k, i, j* are indexes defining the states.

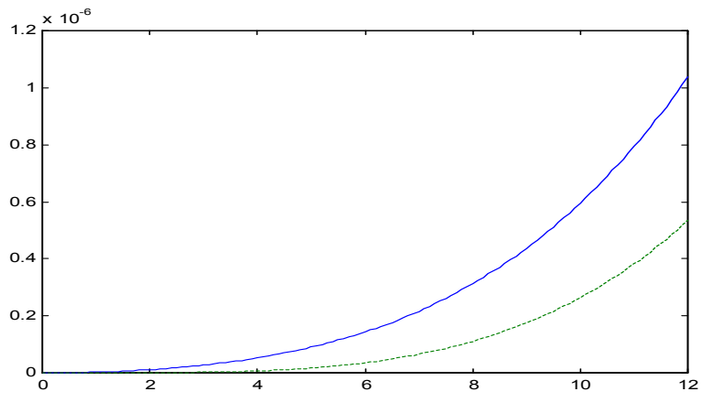


Fig. 8. Flight risk by considering (state An included - solid blue line ) or neglecting the effects of anomalies (green dashed line).

As a result, the general model – describing the real interactions between different types of failures, distinguishing common and depending failures – could be reduced to a simple model.

The developed model was used for the analysis of the aircraft control. Some results are shown in Figures 8. and 9.

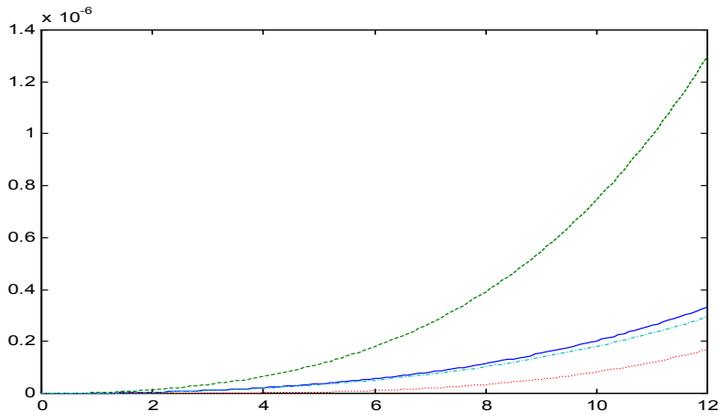


Fig. 9. Probability of appearance of first failures (solid blue line - pilot error (failure), green dashed line - pilot error in case of system anomalies red dashed line - structure failure, blue dashed dot line - structure failure calculated considering the influences of the anomalies).

## 4. Subjective analysis and flight safety

### 4.1 Theoretical background

The major determinative element of the aircraft's conventional control systems is the pilot. Such systems are called as ergatic active endogenous systems [Kasyanov 2007], since the systems are actively controlled by solutions initiated by ergates (Greek ἐργάτης ergatēs - worker), human organism (e.g. nervous cells). So the control solution becomes from inside the system, from the operator. Such effects are called often as endogenous feedback or endogenous dynamics (Banos, Lamnabhi-Lagarrigue & Montoya, 2001; Fliens et all, 1999, Nieuwstadt 1997]. Because pilots make their decision upon their situation awareness, knowledge, practice and skills, e.g. on the subjective way, the system would be also subjective. Beside human robust behaviors and individual possibilities, pilots – in certain circumstances – should also make decisions, even if the information for an appropriate reaction is limited.

Safety of active systems is determined by risks initiated by subjects being the central elements of the given system. For example, flight safety is the probability that a flight happens without an accident. Aircraft are moving in the three dimensional space, in function of their aerodynamic characteristics, flight dynamics, environmental stochastic disturbances (e.g. wind, air turbulence) and applied control. Pilots make decision upon their situation awareness. They must define the problem and choose the solution from their resources, which makes human controlled active systems endogenous. Resources are methods or technologies that can be applied to solve the problems (Kasyanov, 2007). These could be classified into the so-called (i) passive (finance, materials, information, energy - like aircraft control system in its physical form) and (ii) active (physical, intellectual, psycho-physiological behaviors, possibilities of subjects) resources. The passive resources are therefore the resources of the system (e.g. air transportation system, ATM, services provided), while the active resources are related to the pilot itself. Based on these, decision making is in fact the process of choosing the right resources that leads to an optimal solution.

Subjects (like pilots) could develop their active resources (or competences) with theoretical studies and practical lessons. However, the ability of choosing and using the right resources is highly depending on (i) the information support, (ii) the available time, (iii) the real knowledge, (iv) the way of thinking, and (v) the skills of the subject. Such decisions are the results of the subjective analysis.

There is insufficient information on the physical, systematic, intellectual, physiological characteristics of the subjective analysis, as well as on the way of thinking, and making decision of subjects-operators like pilots. Only limited information is available on the time effects, possible damping the non-linear oscillations, the long-term memory, which makes the decision system chaotic.

Flight safety can be evaluated by the combination of subjective analysis and aircraft motion models.

At first, the pilot as subject (Σ) must identify and understand the problem or the situation ($S_{i,}$), then from the set of accessible or possible devices, methods and factors ($S_p$) must choose the disposable resources ( $R^{disp}$ ) available to solve the identified problems, to finally decide and apply the required resources ( $R^{req}$ ) (Kasyanov 2007) (Fig.10.). For this task, the pilot applies its active and passive resources. The active resources will define how the passive resources are used:

$$R_a^{req} = f\left(R_p^{req}\right) \tag{22}$$

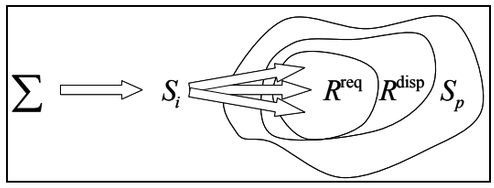


Fig. 10. Pilot decision – action process (endogenous dynamics) in aircraft operation (control) system.

Instead of the function between the resources (22), the literature often uses the velocity of transferring the passive resources into the actives:

$$v_a^{req} = f_v\left(v_a^{req}\right)v_a^{req}, \tag{23}$$

where

$$v_a^{req} = \frac{dR_a^{req}}{dt}, \qquad v_p^{req} = \frac{dR_p^{req}}{dt}, \tag{24}$$

and in simple cases

$$f_v = \frac{\partial R_a^{req}}{\partial R_p^{req}}. \tag{25}$$

It is clear that the operational processes can be given by a series of situations: pilot identifies the situation ($S_i$,), makes decision, controls ( $R_a^{req}$ ), which transits the aircraft into the next situation ($S_j$,). (The situation $S_j$, is one of the set of possible situations). This is a repeating process (Fig. 11.), in which the transition from one situation into another depends on (i) the evaluation (identification) of the given situation, (ii) the available resources, (iii) the appropriate decision of the pilot, (iv) the correct application of the active resources, (v) the limitation of the resources and (vi) the affecting disturbances.

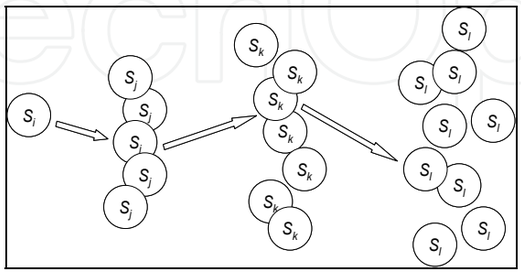


Fig. 11. Situation chain process of aircraft operational process as a result of an active subjective endogenous control.

The situation chain process can be given by the following mathematical formula:

$$c(t): \quad \left(x_0, t_0, \omega\left(t_f \in [t_0, t_0+\tau]\right); R^{disp}(t_0), R^{req}(t_0), \ldots\right), \tag{26}$$

or in a more general approach:

$$c(t): \quad \left(P: \sigma_0(t_0) \to \sigma_j\left(t_f \in [t_0, t_0+\tau]\right) \in S_f \subset S_a, R^{disp}(t_0), R^{req}(t_0), \ldots\right); \tag{27}$$

where $x_0$ is the vector of parameters at the initial (actually starting) state at $t_0$ time; $\sigma$ gives the state of the system in the given time; $\tau$ defines the available time for the transition of the state vector into the set of $\omega$ not later than $[t_0, t_0+\tau]$; $P$ are the problems how to transit the system from the initial state into the one of the possible state $S_f \subset S_a$ not later than $\tau$.

During a flight, one flight situation is followed by another. Therefore, the aircraft flight operational process with continuous state space and time can be approximated by the stochastic process with continuous time and discrete state space, flight situations. This means that a flight is a typical situation chain process. (This is a basis for using the stochastic model of flight risk - see 2.2. point.)

### 4.2 Using the developed model to investigation of the aircraft landing

Final approach and landing are the most dangerous phases of flights. It is even a more significant problem for personal flights, controlled by less-skilled pilots.

The developed method using the subjective analysis to the flight safety evaluation was applied to investigate a landing procedure of a small aircraft.

In this investigation, no side wing, and no lateral motion were considered. By using the trajectory reference system – in which the $x$ axis shows the direction of the wind, $z$ axis is

perpendicular to $x$ in the local vertical plane, while centre of the coordinate system is located in the aircraft's centre of gravity – the motion of the aircraft could be given by the motion and the rotation of its center of gravity (Kasyanov 2004):

$$m\frac{dV}{dt} = T(V,z,t) - W\sin\theta - D(V,z,t) \ , \tag{28.a}$$

$$mV\frac{d\theta}{dt} = L(V,z,t) - W\cos\theta \ , \tag{28.b}$$

$$I_y\frac{dq}{dt} = M(\alpha,q,V,z,t) \ . \tag{28.c}$$

Due to the applied control, the trust (*T*), the lift (*L*), the drag (*D*) and the aerodynamic moment (*M*) are all clearly depending on time. The altitude (*z*) has also an influence on the variable above, through the ground effect. Mass (*m*) and therefore the weight (*W*) of the aircraft are assumed to be constant. The aircraft's velocity (*V*) and pitch rate (*q*) describes the motion, while the flight path angle (or descent angle $\theta$) gives the position of the aircraft. The angle of attack ($\alpha$) is the difference between the pitch attitude, $\vartheta$ and flight path angles:

$$\alpha = \upsilon - \theta \ . \tag{29}$$

The pitch rate and the modification of the altitude could be easily given by:

$$q = \frac{d\upsilon}{dt} \ , \tag{30}$$

$$\frac{dH}{dt} = V\sin\theta \ . \tag{31}$$

According to the flight operational manuals and airworthiness requirements, limitations (mi - minimum and ma - maximum) should be applied on the velocity, the descent angle and the decision altitude:

$$V \in \left[V_{mi}^{*}, V_{ma}^{*}\right], \tag{32.a}$$

$$\theta \in \left[\theta_{mi}^{*}, \theta_{ma}^{*}\right], \tag{32.b}$$

$$H \geq H_{Dmi}^{*} \ . \tag{32.c}$$

A simple assumption could be applied: during an approach, pilots should decide whether to land or to make a go-around. For this decision they need time, which is the sum of (i) the time to understand and evaluate the given situation, $\sigma_k$, (ii) the time for decision making and (iii) the time to react (covering also the reaction time of the aircraft for the applied decision) (Kasyanov 2007):

$$t^{req} = t_{ue}^{req}(\sigma_k) + t_{dec}^{req}(S_a) + t_{react}^{req}(\sigma_k, S_a) \ . \tag{33}$$

Here $\sigma_k$ defines all possible situations (e.g. $\sigma_1$ might be the situation of landing at first approach without any problems, $\sigma_2$ could be related to the situation when the under carriage system could not be opened, $\sigma_3$ might stand for a landing on the fuselage, $\sigma_5$ for go-around, or $\sigma_5$ for a successful landing after second approach).

$S_a$ is the chosen solution from the set of possible solutions. It is clear that all solutions have a limited drawback, such as extra cost, or extra fuel.

The subjective factor of pilots might be introduced with the use of the ratio of the required and disposable resources (Kasyanov 2007):

$$\overline{r}_k = \frac{R^{req}(\sigma_k)}{R^{disp}(\sigma_k)} = \overline{t}_k = \frac{t^{req}(\sigma_k)}{t^{disp}(\sigma_k)} \ . \tag{34}$$

In this case, an endogenous index can be defined as

$$\varepsilon_k(\sigma_k) = \frac{\overline{r}_k}{1-\overline{r}_k} = \frac{t^{req}(\sigma_k)}{t^{disp}(\sigma_k) - t^{req}(\sigma_k)} \quad or \quad \varepsilon_k(\sigma_k) = \frac{t^{req}(\sigma_k) + t^{dec}(S_a)}{t^{disp}(\sigma_k) + t^{dec} - t^{req}(\sigma_k)} \ , \tag{35}$$

where $t^{dec}(S_a)$ is a time required to recognize the set of alternative strategies.

Naturally, we can assume that pilots are able to evaluate the consequences of their decisions, and therefore they can evaluate the risk of the applied solutions. Such evaluation can be defined as the subjective probability of situations: $P(\sigma_k)$, canonic distribution of which as the distribution of canonic assemble of the preferences is assumed to hold the following form:

$$p(\sigma_k) = \frac{P^{-\alpha}(\sigma_k) e^{-\beta\varepsilon_k(\sigma_k)}}{\sum_{q=1}^{2} P^{-\alpha}(\sigma_q) e^{-\beta\varepsilon_k(\sigma_q)}} \ , \tag{36}$$

where $p(\sigma_k)$ describes the distribution of the best alternatives from a negative point of view.

The time-depending coefficients $\alpha$ and $\beta$ should be chosen in a way to model the endogenous dynamics, model the subjective psycho physiological personalities of pilots. The qualities of the pilots are depending on different factors including "periodical" incapacity to make decisions that increases while getting closer to the decision time (altitude) of go-around.

The (36) has special features: in case of $\overline{t}_k = \frac{t^{req}(\sigma_k)}{t^{disp}(\sigma_k)} \to 0$ preferences are determined by the subjective probability, $P(\sigma_k)$, only, and in case $\overline{t}_k \to 1$, the preference turn into zero. The (36 ) comes from the solution of the following function:

$$\Phi_p = -\sum_{k=1}^{N} p(\sigma_k)\ln p(\sigma_k) - \beta\sum_{k=1}^{N} p(\sigma_k)\varepsilon_k(\sigma_k) - \alpha\sum_{k=1}^{N} p(\sigma_k)\ln P(\sigma_k) + \gamma\sum_{k=1}^{N} p(\sigma_k) \ . \quad (37)$$

A special feature of this function is that the structure of the efficiency function includes the logarithm of the subjective probability:

$$\eta_p = -\sum_{k=1}^{N}\left(\alpha \ln P(\sigma_k) + \beta\varepsilon(\sigma_k)\right)p(\sigma_k) . \quad (38)$$

The complexity of decision making could be characterized by the uncertainties or the pilots' incapacity to make decisions, which is increasing while getting closer to the minimum decision altitude, $H^*_{Dmi}$. To make decisions, the pilots must overcome their "entropic barrier", $H_p$. The rate of incapacity could be defined with the norm of entropy:

$$\bar{H}_p = \frac{H_p}{\ln N} \ . \quad (39)$$

Figure 12. shows a simplified decision making situation at an approach about the go-around [Kasyanov 2004, 2007]. At $t_0, x_0$, $S_a : (\sigma_1, \sigma_2)$ indicates the set of alternative situations with the distribution of preferences $p(\sigma_1)$ and $p(\sigma_2)$ (where $\sigma_1$ indicates the landing and $\sigma_2$ defines the go-around).

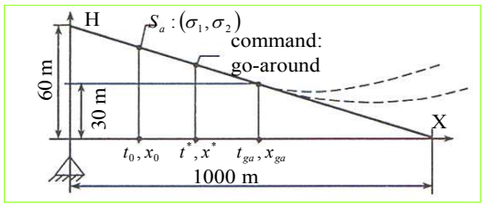


Fig. 12. Final phase of aircraft approach.

The preferences are oscillating, because of the exogenous fluctuation (while decision altitude is getting closer) and the endogenous processes (depending on the uncertainties in the situation awareness and operators (pilots) incapacity to make decisions). If pilots are able to overcome their entropy barrier up to command for go-around (reaching the decision minimum altitude), $t^*, x^*$, then they could make a decision. Due to this decision, the set of situations, $S_a$, can be given with the followings:

$$\begin{array}{l} S_a : (\sigma_2); p(\sigma_2) \\ t \prec t^* \\ p(\sigma_1) + p(\sigma_2) = 1 \end{array} \Rightarrow \begin{array}{l} S_{a1} : (\sigma_2); p(\sigma_2) = 1; p(\sigma_1) = 0 \\ \\ S_{a2} : (\sigma_1); p(\sigma_1) = 1; p(\sigma_2) = 0 \\ t \geq t^* \end{array} \quad (40)$$

If pilots are not able to overcome their entropy barrier before reaching $t^*, x^*$, the flight situation would become more complex, and therefore the possibility to perform a go-around (case $\sigma_2$) might be even out of the possible set of situations.

### 4.3 Modeling the human way of thinking and decision making

A human as "biomotoric system" uses the information provided by sense organs (sight, hearing, balance, etc.) to determine the motoric actions (Zamora, 2004). From a piloting point of view, balance is the most important from the human sense organs. (As known, pilots are flying upon their "botty" for sensing the aircraft's real spatial position, orientation and motion dynamics (Rohacs, 2006).) The sense of balance (Zamora, 2004) is maintained by a complex interaction of visual inputs (the proprioceptive sensors being affected by gravity and stretch sensors found in muscles, skin, and joints), the inner ear vestibular system, and the central nervous system. Disturbances occurring in any part of the balance system, or even within the brain's integration of inputs, could cause dizziness or unsteadiness.

In addition to this, human has another sensing, kinesthesia (Zamora, 2004) that is the precise awareness of muscle and joint movement that allows us to coordinate our muscles when we walk, talk, and use our hands. It is the sense of kinesthesia that enables us to touch the tip of our nose with our eyes closed or to know which part of the body we should scratch when we itch. This type of sensing is very important in controlling an aircraft and moving in 3D space. (Some scientists believe that future aircraft control system must be operated by thumbs, as the new generation is trained on video-games such as "Game Boy" (Rohacs, 2006).)

The main element of the "human biomotoric system" is the human brain that is the anteriormost part of the central nervous system in humans as well as the primary control center for the peripheral nervous system.

The human brain (Russel, 1979; Davidmann, 1998). is a very complex system based on the net of brain cells called as neurons that specialize in communication. The brain contains circuits of interconnected neurons that pass information between themselves.

The neurons contain the dendrites, cell body and axon. In neurons, information passes from dendrites through the cell body and down the axon (Russel, 1979; Davidmann, 1998).

Principally, transmission of information through the neuron is an electrical process. The passage of a nerve impulse starts at a dendrite, it then travels through the cell body, down the axon to an axon terminal. Axon terminals lie close to the dendrites of neighboring neurons.

From control theory point of view, the most important behavior of human brain is the memory, namely learning, memorizing and remembering (Receiving, Storing and Recalling). Generally, human beings are learning all the time, storing information and then recalling it when it is required (Davidmann, 1998). After the investigation of human thinking, including recognition, information analysis, reasoning, decision support (Rohacs, 2006; 2007) the human way of thinking is found to be have the following behaviors:

- syntactic and semantic processing of the sensed information,
- working on the basis of large net of small and simplified articles (neurons),
- using the complex system oriented approach,
- making parallel thinking and activity,
- learning (synthesis of the new knowledge),
- model-formation and using the models (including verbal models applied in learning processes and complex mathematical representation),
- long-term memory,

- tacit knowledge (took in practice),
- intentional thinking (goal and wish),
- intuition (subconscious thinking),
- creativity (finding the contexts),
- innovativity (making originally new minds, things),
- unexpected values can be appeared,
- jumping from quantity to quality.

Seeing all the features listed above, it is clear that human thinking and decision making is a very complex process, containing some chaotic effects.

There is not enough information on the physical, systematic, intellectual, psychophysiology, etc. characteristics of the subjective analysis, about the way of thinking and making decision of subjects-operators like pilots. Only limited information is available on the time effects, possible damping the non-linear oscillations, long term memory, etc. making the decision system chaotic.

Professor Kasyanov introduced a special chaotic model (Kasyanov, 2007) based on the modified Lorenz attractor (Stogatz, 1994) for modeling the endogenous dynamics of the described process.

$$\begin{aligned} \frac{dX}{dt} &= aY - bZ - hX^2 + f(t); \\ \frac{dY}{dt} &= -Y - XZ + cX - mY^2; \\ \frac{dZ}{dt} &= XY - dZ - nZ^2. \end{aligned} \tag{41}$$

where *a, b, c, d, h, m, n* are the constants while *f* takes into account the disturbance. (In case of $h=m=n=0$ and $f(t)=0$ the model turns into the classic form of Lorenz attractor.)

Principally, there are no strong arguments explaining the use of Lorenz attractor to model the human way of decision making (human thinking) (Dartnell, 2010; Krakovska, 2009), but the results of application are close to real situations.

### 4.4 Results of investigations

Professor Kasyanov investigated various model types, and evaluated the model parameters (Kasyanov, 2007). For a medium sized aircraft (weight of aircraft, $W = 10^6$ N; wing area, S = 100 m$^2$; wing aspect ratio A = 7; thrust $T = 9.4 \times 10^4$ N; and velocity V = 70 m/sec) with commercial pilots, he recommended to use the following values: a=8; b=8; c=20; d.43; f=0.8; h= 0.065; m=0.065; n=0.065.

Using these parameters, the subjective probabilities might be chosen as $P(\sigma_1) = 0.53$, $P(\sigma_2) = 0.6$ and $\varepsilon_1 = 5.5 + 0.01t$, $\varepsilon_2 = 5.4 + 0.04t$ take into account the decreasing difference in the required and the available time for the decision. The typical results of using the described model are shown in the Figure 13., demonstrating the chaotic character of decision making.

In this example, the figures demonstrate that pilots are unfixed for a period of about 10 sec, during which their preferences (A, B) are changing by sudden oscillations and the H

entropy at the beginning is rather high. If the limit for the entropy would be 0.7 (that is still quit high) then decisions could be made in about 10 sec. This means that pilots will not able to do that according to the Figure 12.

If the parameters are set to a=10; b=10; c=35; d=1; f=0; h= 0.065; m=0.065; n=0.065 and $P(\sigma_1)=0.53,\quad P(\sigma_2)=0.6$, then (see Figure 14) the entropy would quickly decrease and the decision could be made in about 3 sec. According to the ICAO requirements, time $t=t_{ga}-t^*$ (see Figure 12.) should not be less than 3.16 sec. Therefore, if the situation presented in the Figure 12. appears before $t_0, x_0$, then the right decision could be made.

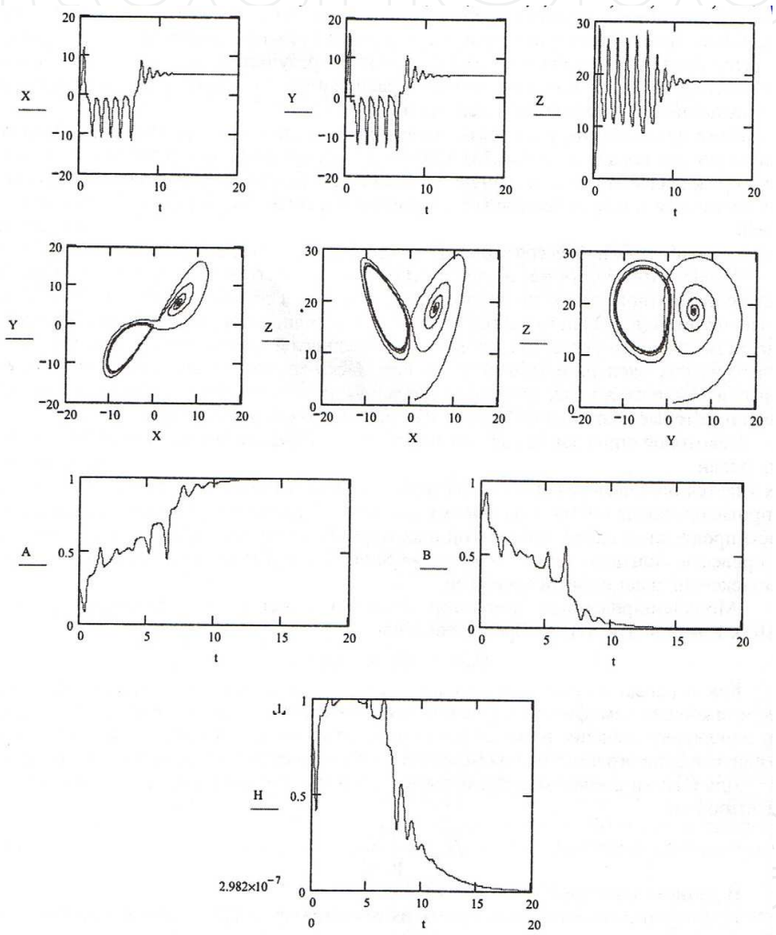


Fig. 13. Results of using the developed model to landing of a medium sized aircraft.

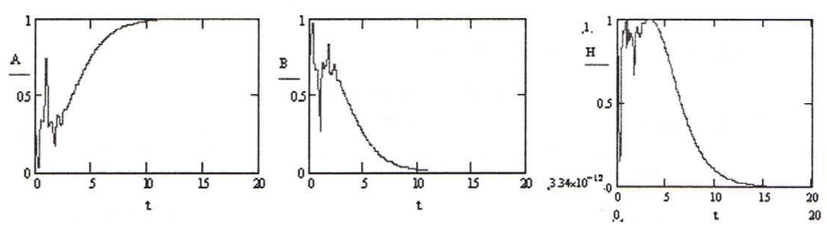


Fig. 14. Results, when the parameters are chosen for well-skilled pilots.

From the results of using the developed model to the landing phase of a small aircraft (such as analyzed in the Hungarian national projects SafeFly: development of the innovative safety technologies for a 4 seats composite aircraft and EU FP7 project PPlane: Personal Plane: Assessment and Validation of Pioneering Concepts for Personal Air Transport Systems, Grant agreement no.233805) several important conclusions had been made (Rohacs et all, 2011; Rohacs & Kasyanov, 2011; Rohacs, 2010).

During the final approach, the common airliner pilots require about three times more time for making decision on go-around than the well practiced colleagues.

Using the developed model and condition defined by Figure 12, the descent velocity of a small aircraft could be determined to about 100 km/h for airliner common pilots, and 75 km/h for those of less-skilled.

In this case, the airport can be designed with a landing distance of less than 600 m (runway about 250 - 300 m) and a protected zone under the approach (to overfly the altitude of 100 m) of about 1500 m. These characteristics enable to place small airports close / closer to the city center.

## 5. Conclusions

This chapter introduced the subjective analysis methodology into the investigation of the real flight situation, flight safety. The subject, as pilot operator generates his decision on the basis of his subjective situation analysis depending on the available information and his psycho-physiological condition. The subjective factor is the time available for the decision of the given tasks.

After the general discussion on flight safety, its metrics and accident statistics, an original approach was introduced to study the role of human factors in flight safety. The deterministic or stochastic models of flight safety are not included clearly the subjective behaviors of human operators. However, the subjective analysis may open a new vision on the flight safety and may result to improve the aircraft development methods and tools.

The subjective decision making of pilots was modeled by the modified Lorenz attractor that needs further investigation and explanation. The applicability of the developed methodology was applied to study the small aircraft final approach and landing. It demonstrates that the model is suitable to investigate the difference between the well trained and less-skilled pilots. The model helped in the definition of the aircraft and airport characteristics for the personal air transportation system.

This work is connected to the scientific program of the "Development of the innovative safety technologies for a 4 seats composite aircraft - SafeFly" (NKTH-MAG ZRt. OM-000167/2008) supported by Hungarian National Development Office and Personal Plane - PPLANE Projhect supported by EU FPO7 (Contract No - 233805) and the research is supported by the Hungarian National New Széchenyi Plan (TÁMOP-4.2.2/B-10/1-2010-0009)

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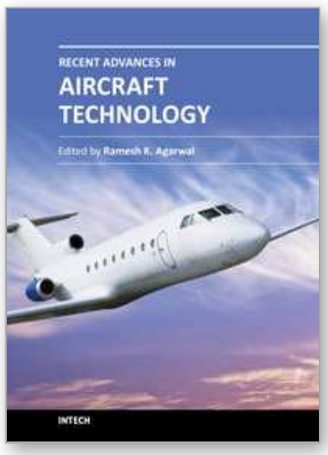


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