International Journal of Computer and Information Technology (ISSN: 2279 – 0764)
Volume 04 – Issue 02, March 2015

Selected Methods of Aviation Safety Estimation, including use of Fuzzy Logic Inference Systems

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Abstract— **In this article authors presented selected methods of risk factors and safety estimation in air transport including use of fuzzy logic inference systems (fuzzy expert inference systems are under consideration)**

Keywords—safety; aviation; risk factors; fuzzy inference systems.

I. INTRODUCTION

Identification and analyzing of threats are active methods of risk management in air transport constructions. Flight safety estimation is carried out by statistic and probabilistic criteria, neutral network and fuzzy expert inference systems.

Depend on the criterion, methods and flying safety rate are defined and allow assessing transport system safety [1,2,7].

The system safety assessment and causes threat analyze possibility provides safety strategy management, flight planning and flight training program improvement [4].

Air transport safety is described as system feature that ensures work with no accidents and undesirable situations. Part of the publication, concerns selected methods of aviation safety estimation, but in composite aviation constructions, was presented in International Conference on composites and nano engineering ICCE-22.

II. METHODS OF AVIATION SAFETY ESTIMATION

Aviation safety estimation is carried out by statistic, probabilistic methods (models) and neutral network and fuzzy logic systems.

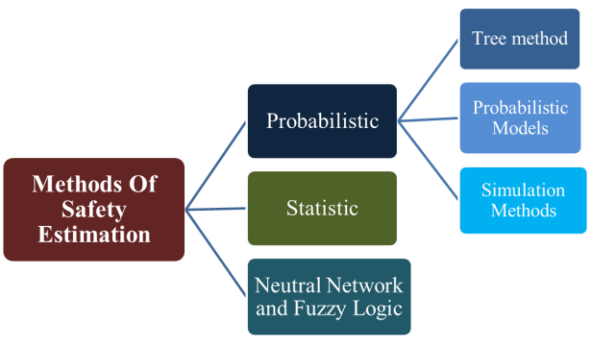

Figure 1: Classification of aviation safety estimation methods

A. *Probabilistic method*

Probabilistic method consists of: tree method, probabilistic models and simulation methods.

Decomposition of an occurrence (for example aircraft accident) into cause and effect chain is called tree damage method. Specified logical operators are used to demonstrate the method. Bell Telephone Laboratories was the first company that used the tree method in rocket ignition reliability analysis.

Operators symbols are presented on Figure 2, which are used in damages tree method [3].

Nu.	Operator name	Operator symbol	Operator description
1.	Operator I logical product		The output signal appears only when all input signals are provided.
2.	Operator OR logical sum		The output signal appears only when one or more input signals are provided.
3.	The excluding operator		The output signal appears only when one input signals is provided.

Figure 2: Operator symbols used in tree damage method

<u>Probabilistic models</u> are used to evaluate flight safety (with air threat consideration, like aircraft damage or air space interferences) and using of redundant systems to avoid aircraft accidents. Markow processes are mostly used in probabilistic analysis.

Flight of the aircraft is reduced to three states, respectively, which assign probabilities to stay in these states (Figure 3), where:

$P_1(t)$ - undisturbed flight probability;

$P_2(t)$ - undisturbed flight probability with possibility of redundancy systems use (rescue systems);

$P_3(t)$ - probability of malfunction or plane crash;

λ, μ - transition between states intensity.

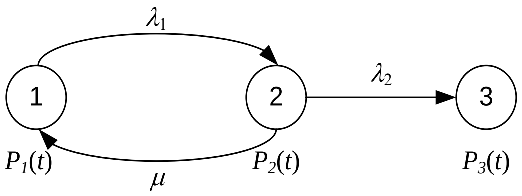

Figure 3: Aircraft flight three-states model

For that kind of model of flight we can create Kołmogorow differential equations system:

$$\begin{cases} P_1'(t) = -\lambda_1 P_1(t) + \mu P_2(t) \\ P_2'(t) = \lambda_1 P_1(t) - (\mu + \lambda_2) P_2(t) \\ P_3'(t) = \lambda_2 P_2(t) \end{cases} \tag{1}$$

In result of performed calculations:

$$\begin{cases} P_1(t) = \dfrac{r_1 + \lambda_1}{r_1 - r_2} e^{r_2 t} - \dfrac{r_2 + \lambda_1}{r_1 - r_2} e^{r_1 t} \\ P_2(t) = \dfrac{(r_1 + \lambda_1)(r_2 + \lambda_1)}{\mu (r_1 - r_2)} \left[e^{r_2 t} - e^{r_1 t} \right] \\ P_3(t) = \dfrac{\lambda_2 (r_1 + \lambda_1)(r_2 + \lambda_1)}{\mu (r_1 - r_2)} \left[\dfrac{1}{r_2} e^{r_2 t} - \dfrac{1}{r_1} e^{r_1 t} \right] - \dfrac{\lambda_2}{\mu r_1 r_2} (r_2 + \lambda_1)(r_1 + \lambda_1) \end{cases} \tag{2}$$

where:

$$r_1 = \frac{-(\lambda_1 + \lambda_2 + \mu) - \sqrt{(\lambda_1 - \lambda_2)^2 + 2\mu(\lambda_1 + \lambda_2) + \mu^2}}{2}$$
$$r_2 = \frac{-(\lambda_1 + \lambda_2 + \mu) + \sqrt{(\lambda_1 - \lambda_2)^2 + 2\mu(\lambda_1 + \lambda_2) + \mu^2}}{2} \tag{3}$$

Presented solution meets the initial conditions. The sum of calculated probabilities equals one. The last necessity is process of calculated functions checking for high value of *t* ($t \to \infty$).

$$\begin{aligned} \lim_{t\to\infty} P_1(t) &= \frac{r_1 + \lambda_1}{r_1 - r_2} \lim_{t\to\infty} e^{r_2 t} - \frac{r_2 + \lambda_1}{r_1 - r_2} \lim_{t\to\infty} e^{r_1 t} \\ \lim_{t\to\infty} P_2(t) &= \frac{(r_1 + \lambda_1)(r_2 + \lambda_1)}{\mu (r_1 - r_2)} \left[\lim_{t\to\infty} e^{r_2 t} - \lim_{t\to\infty} e^{r_1 t} \right] \\ \lim_{t\to\infty} P_3(t) &= \frac{\lambda_2 (r_1 + \lambda_1)(r_2 + \lambda_1)}{\mu (r_1 - r_2)} \left[\frac{1}{r_2} \lim_{t\to\infty} e^{r_2 t} - \frac{1}{r_1} \lim_{t\to\infty} e^{r_1 t} \right] - \frac{\lambda_2}{\mu r_1 r_2} (r_2 + \lambda_1)(r_1 + \lambda_1) \end{aligned} \tag{4}$$

Because:

$$r_1 = -\frac{(\lambda_1 + \lambda_2 + \mu) + \sqrt{(\lambda_1 + \lambda_2 + \mu)^2 - 4\lambda_1 \lambda_2}}{2} < 0$$
$$r_2 = -\frac{(\lambda_1 + \lambda_2 + \mu) - \sqrt{(\lambda_1 + \lambda_2 + \mu)^2 - 4\lambda_1 \lambda_2}}{2} < 0 \tag{5}$$

so:

$$\lim_{t\to\infty} e^{r_1 t} = \lim_{t\to\infty} e^{\frac{-(\lambda_1+\lambda_2+\mu) - \sqrt{(\lambda_1-\lambda_2)^2 + 2\mu(\lambda_1+\lambda_2) + \mu^2}}{2} t} = 0$$
$$\lim_{t\to\infty} e^{r_2 t} = \lim_{t\to\infty} e^{\frac{-(\lambda_1+\lambda_2+\mu) + \sqrt{(\lambda_1-\lambda_2)^2 + 2\mu(\lambda_1+\lambda_2) + \mu^2}}{2} t} = 0 \tag{6}$$

And follow that:

$$\lim_{t\to\infty} P_1(t) = 0$$
$$\lim_{t\to\infty} P_2(t) = 0$$
$$\lim_{t\to\infty} P_3(t) = -\frac{\lambda_2}{\mu r_1 r_2} (r_2 + \lambda_1)(r_1 + \lambda_1) = 1 \tag{7}$$

Designating forecasting time interval to reach absorbing stage is also really interesting subject.

Simulation is an experimental method of systems models analysis. Important feature in this method is making repeated attempts to obtain data that allow getting material representation of studied states sequence. The aim of research determines type and way of state representation.

Depending on types of mathematic models a simulation can be divided on:

- deterministic simulation,
- stochastic simulation.

Systems analyzing by simulation method consist of few stages [1]:

- mental model conception of the system M_0,
- M_0 mathematical model representation $M(M_0)$ of the system: $f: M_0 \to M(M_0)$,
- $M(M_0)$ transition of mathematical model representation into simulation model $M_S[M(M_0)]$ of the system:

$$g: M(M_0) \to M_S[M(M_0)], \tag{8}$$

- conducting of simulating experiment and getting the results providing series of stages simulated model $M_S[M(M_o)]$ as set of values, elaboration of the results as logical or mathematical relations,
- model verification accomplished based on results reliability analyzing and assessing, simulation model acceptance or modification.

B. *Statistic estimation method*

In statistic estimation method, absolute and relative time indicators are provided.

Basic flight safety indicators recommended by ICAO (International Civil Aviation Organization) are (K_T) and (K_L) which describe a number (n_k) of flight accidents attributable to 100 000 hours (time) of flight or 100 million kilometers of flight (distance) [1]:

$$K_T = \frac{n_k}{T}10^5 \; ; \quad K_N = \frac{n_k}{N}10^5 \; ; \quad K_L = \frac{n_k}{L}10^8 \; ; \tag{9}$$

or ratio of fatalities in flight accidents K_l attributable to 1 million transported passengers or 100 million kilometers flew by passengers [1]:

$$K_{l_1} = \frac{l_{pas}}{A_{pas}}10^6 \; ; \quad K_{l_2} = \frac{l_{pas}}{A_{pas-km}}10^8 \; ; \tag{10}$$

where:

T - total flying time in hours of aircraft at considered period of time;

N - total number of aircraft's flights in considered period of time;

L - flying time in kilometers of aircraft at considered period of time;

l_{pas} - number of casualties at the specific period of time;

A_{pas} - number of transported passengers at the specific period of time;

$A_{pas\text{-}km}$ - number of kilometers flew by passengers the specific period of time.

Partial indicators are also used in countries – the ICAO members. The indicators describe the phases of aircraft flight like: take off, landing, etc.

C. *Neutral network and fuzzy logic systems*

Neutral network and fuzzy logic systems can be used to aircraft devices future state forecast. The forecast is based on current and future states of the devices. Use of neutral network eliminate necessity of solving problems and provides aircraft devices behavior inference. The inference is based on gathered in data bases information. Neutral network consists of neutrons. Each neuron has only one output and unlimited inputs.

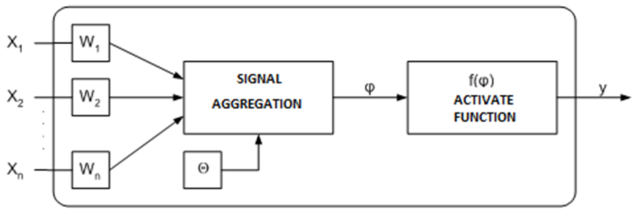

Figure 4: Neuron structure: X – inputs, y – output, w – connection weight, Θ – barrier value

Each single neuron realizes transformation of input data into output signal according to following equation:

$$y = f(\varphi) = f_T(A(x_i, w_i), \Theta) \, , \tag{11}$$

where: A – aggregation function.

Complexity of the systems used by people lead to difficulties with their aviation safety determination with traditional mathematical and statistical methods. One of proposed solution is use of fuzzy inference systems which are already successfully applied in many technical branches, including SMS (Safe Management Systems) [10][12] and CRM (Crew Resource System) [14][15].

Typical fuzzy inference system consists of fuzzy sets (membership functions). Those sets and membership functions are characteristic for fuzzy logic and provide opportunity to use the data in fuzzy inference systems.

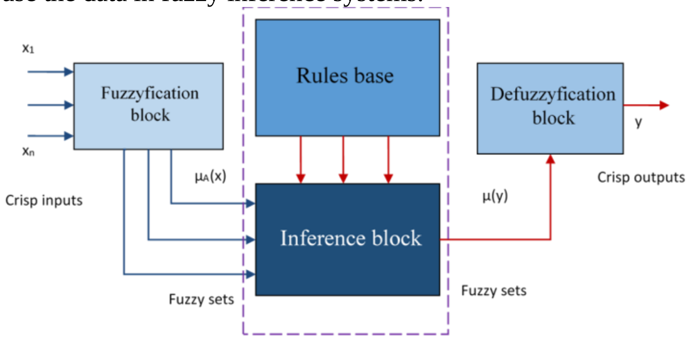

Figure 5: Typical fuzzy inference system

The fuzzy inference system should be characterized by the following features:

- correctness of the system - the system must ensure a high level of published expertise.

This is very important reason to for it is created. The correctness of the system says that it gives good results to solve the tasks in time allowed and has strategies to enable imitating knowledge and expert intuition, often as a result of many years of experience;

- universality - the ability to solve a large class of tasks in this category. To manifest this ability, the system should not contain many rigid, previously prepared solutions, but a large number of rules including a enough wide range of algorithms for the domain problem;

- complexity- is naturally determined by the field in which it is made.

Evaluation of system complexity is possible in some way by the number of inference rules, the size of the database, etc.

- self-analysis - the system should justify you adopted solution not only globally, but also at every stage, it also means each partial solution. To conduct self-analysis the ability to reconstruct a sequence of reasoning is required [11].

Fuzzy controller is a mathematical model described by linguistic variables and rules that operate on these variables. From the point of view of mathematics fuzzy controller approximates a function implemented by the actual system.

The control process starts from the moment of entering the input values to the fuzzification block, where the data are transferred from crisp into fuzzy (linguistic) value.

The next step is creating rules base and inference execution. The fuzzy inference system inference process uses rules in the form of conditional sentences type of IF...THEN...

They consist of a series of linguistic variables combined with logical conjunctions and fuzzy subsets, e.g.

IF a is A1 AND b is B1 THEN c is C1
IF a is A2 AND b is NOT B2 THEN c is C2 (12)

where: a, b, c so-called linguistic variables, and A1, ..., C2 are fuzzy subsets.

An important distinguishing feature of fuzzy rules from the classics rules of the type IF - THEN is the use of variables describing the fuzzy sets, the occurrence mechanism of determining the degree of membership of an element to the collection and use of operations on fuzzy sets. These factors cause certain consequences in the process of inference.

In the described project MIN-MAX inference method was used:

$$\mu_{A\to B}(x, y)=\max\{\min[\mu_A(x), \mu_B(y)], 1-\mu_A(x)\} \qquad (13)$$

After inference process the system needs to transfer fuzzy output values into crisp once again. Defuzzification block is responsible for this operation. This operation is performed by a defuzzification mechanism, which gives the possibility to perform calculations.

There are many defuzzification methods, the most known are:

- *Middle of Maximum* – MOM;
- *Smallest of Maximum* – SOM;
- *Largest of Maximum* – LOM;
- *Center of Gravity* – COG;
- *Center of Sums* – COS;
- *Height Method* – HM.

In the described system, COG defuzzification method was used, because of its advantages. [5]

$$y^* = \frac{\int y\mu(y)dy}{\int \mu(y)dy}, \quad y^* = \frac{\sum_i \mu(y_i) y_i}{\sum_i \mu(y_i)} \qquad (14)$$

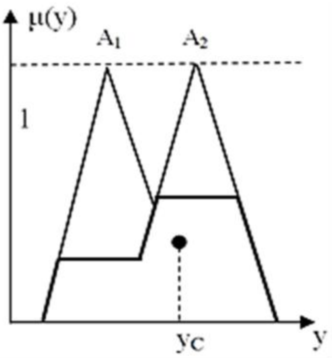

Figure 6: Center of gravity defuzzification method

One of the described example of using fuzzy logic is aircraft braking system pressure controller (based on Cessna 172N aircraft). It has been developed based on Matlab software and Fuzzy Logic Toolbox. Because of the heuristic nature of the fuzzy logic methodology there is no guarantee that the project will operationally well perform. One of the most important aspects therefore is testing and validation of the system performance.

The purpose of the controller is to dose the pressure in the braking system of Cessna 172N based on the two input signals that are the landing speed and the length of the runway. This process aims at utilizing, as efficient as possible, the whole runway length during the landing roll and at the same time reducing the wear of the brakes disks/blocks. This system is also able to assist the pilot in the case of an emergency landing in a chosen area, and would make the pilot able to focus on the approach and a safe landing, during which the controller itself will determine the braking force during the landing. [5,6]

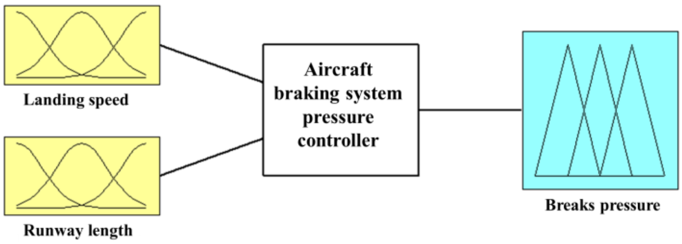

Figure 7: Aircraft braking system pressure controller based on fuzzy logic

Bell-shaped membership functions were used to describe input and output signals.

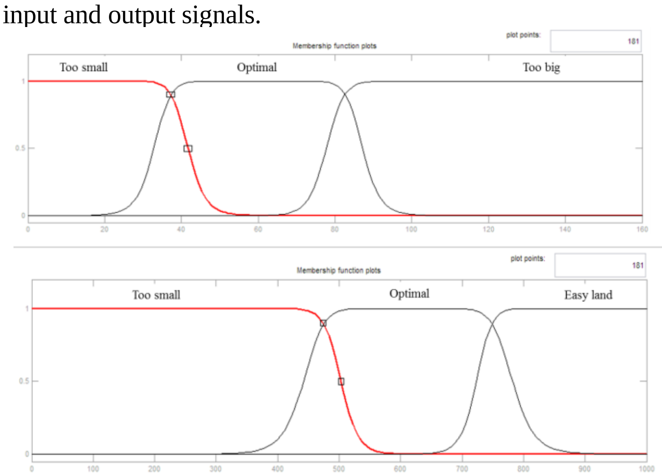

Figure 8: System's input membership functions

The system can improve flight safety especially during landing and allow avoiding mistakes result from incorrect landing speed and brakes pressure. [6,8]

Two data examples, provide system pressure calculations are presented on Figure 9.

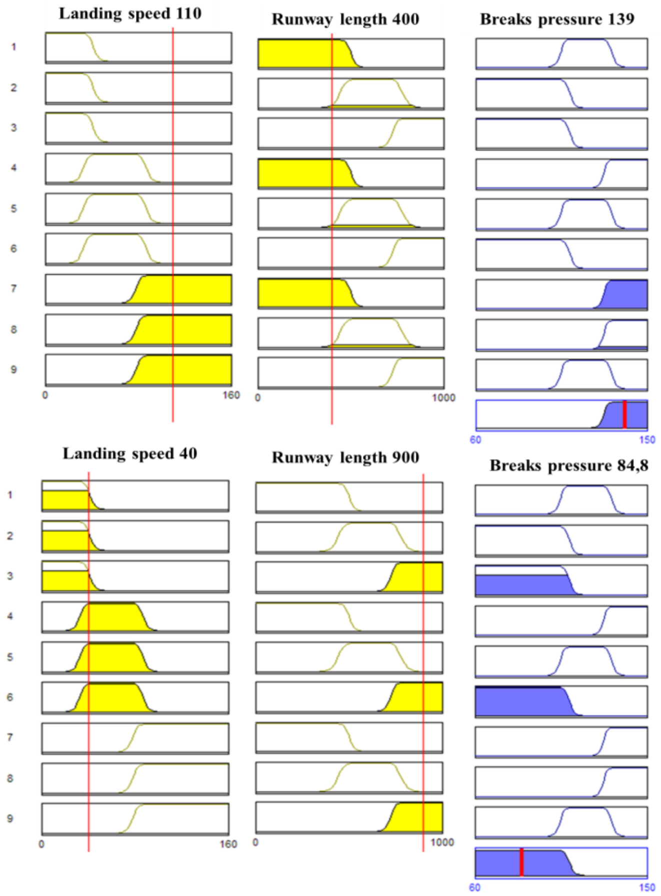

Figure 9: System work data calculations for selected inputs variables

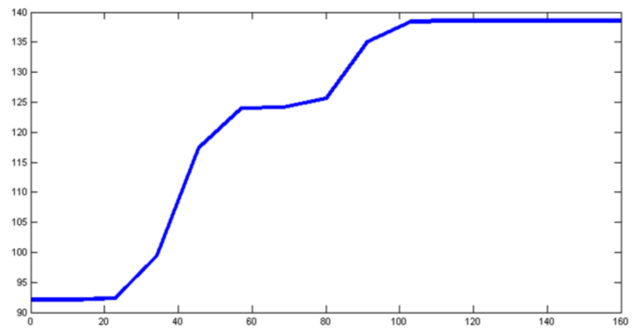

Figure 10: Landing speed and brake system pressure relation

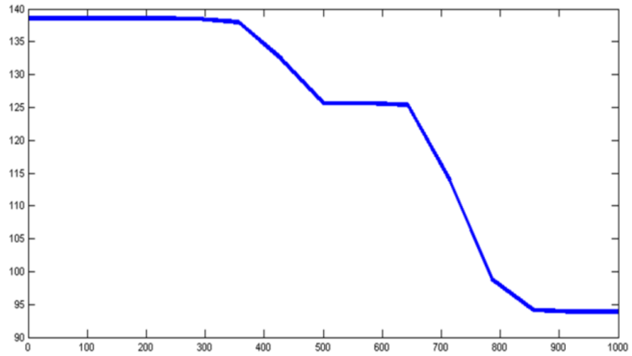

Figure 11: Runway length and brake system pressure relation

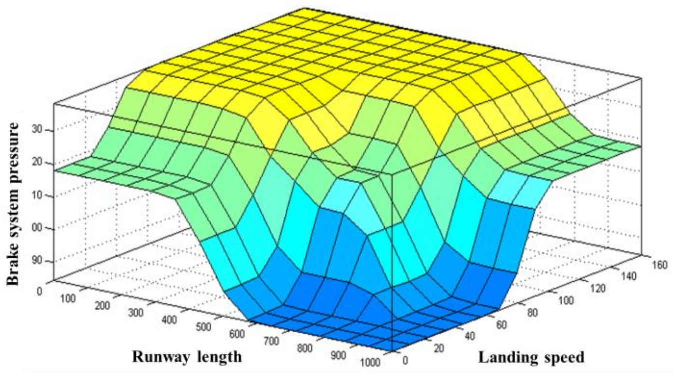

Figure 12: Fuzzy inference system control surface

The second described example of use fuzzy inference system in safety management system (SMS) concerns aircraft crew escape system assistant (proposal to use fuzzy expert pilot decision making system assistant for determining the ejection seats mode in emergency situation during air task). The system was referred in detail on ESREL 2014 (International Safety and Reliability Conference in Wroclaw, Poland). Short description of the system is presented below.

Project was Mamdani type non-adaptive fuzzy inference system with two inputs and one output (MISO - many inputs - single output). The project is shown on Figure 13.

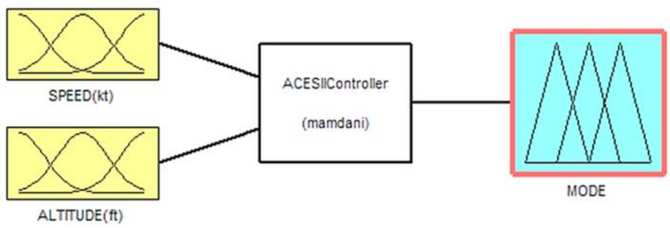

Figure 13. Fuzzy expert aircraft onboard pilot decision making system for ACES II ejection seats mode selection

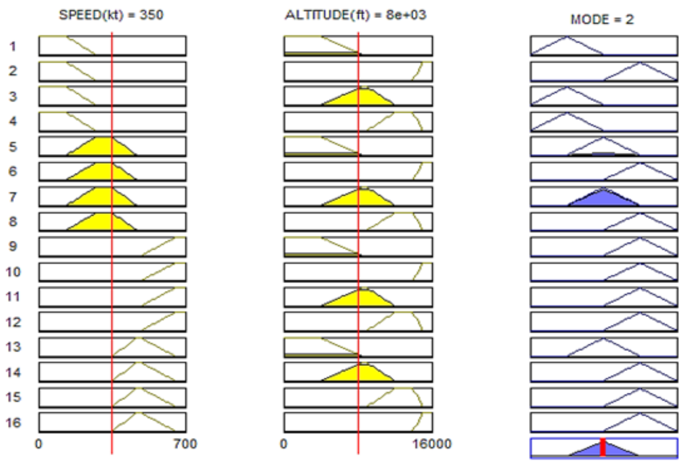

Figure 14. Defuzzification calculation for specific, selected speed and altitude data

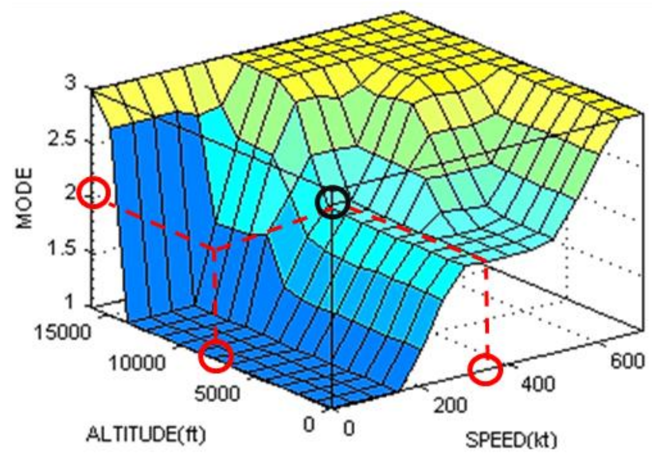

Figure 15. Control surface for specific, selected speed and altitude data

III. Safety risk estimation

Safety risk estimation is defined by:

a) risk occurrences probability,

b) threat risk (other meaning of probability).

According to risk estimation level of threat acceptability can be defined.

Probability of events occuring		
4	POSSIBLE	It can occure once or several times during flight operations
3	SPORADIC	Doesn't occure singly, but occure when few systems are connected
2	VERY RARE	Occure sporadic
1	IMPOSIIBLE	Should not occure in whole fleet life time

Figure 16: Probability of events occurring

Intensity of impact		
4	CATASTROPHIC	Loosing plane and a lot of victims
3	DANGEROUS	A large reduction safety margins which reduce number of victims
2	MORE	Significant reduction safety margins
1	LESS	Disturbances or restrictions with procedures realisation.

Figure 17: Intensity of event's effect

RISK MATRIX

INTENSITY OF IMPACT				
CATASTROPHIC 4	4 – REVIEW	8 –ACTION	12 – ACTION	16 – ACTION
DANGEROUS 3	3 – ACCEPTANCE	6 – REVIEW	9 – ACTION	12 – ACTION
MORE 2	2 – ACCEPTANCE	4 – REVIEW	6 – REVIEW	8 – ACTION
LESS 1	1 – ACCEPTANCE	2 – ACCEPTANCE	3 – ACCEPTANCE	4 – REVIEW
	IMPOSSIBLE - *1*	VERY RARE - *2*	SPORADIC - *3*	POSSIBLE - *4*

EVENT PROBABILITY

Figure 18: Risk acceptance matrix

Based on Figure 18 we can assigned individual levels of acceptance:

- Acceptable - any correction actions are not required,
- Undesirable (tolerated) - risk can be weakened,

Not acceptable - risk must be reduced.

IV. Conclusions

Due to the complexity of the aviation systems and the random nature of the air occurrences, collecting and recording of the air occurrences data is difficult. Appropriate level of detailed incidents description in informatics system is crucial and determines the depth of analysis, including loss of airworthiness of composite structures.

Selected methods of aviation safety estimation are fragmentary, because of article length restrictions and present different approach and estimation aims.

Statistic methods and criteria evaluate, mostly, safety level in the past and do not provide hard base to forecast and solve optimization issues.

Probabilistic methods supports versatility, accurately reflect the aircraft system and influence of internal and external factors on safety.

There is no guarantee that weight vector will be define on minimum global base. That is why optimal neutral network selection could be difficult.

When fuzzy logic is used in consideration issues, there could be a lot of the display errors resulting to high flight speed and breaks pressure. Selection of aggregation and defuzzification methods may be crucial in proper system work. This is only one part of authors research on this issue. More analysis will be provided in next publication series.

Use of optimal and modern forecasting methods [3] and technics cannot replace rational thinking and properly carried out reconnaissance of physical conditions and expected proceeds.

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