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INVESTIGATION OF PROBABILITY CHARACTERISTICS OF THE PILOT VISUAL ACTIVITY STRUCTURE

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Abstract. *Mathematical apparatus to find out regularity for distribution and switching of pilot attention during instrument flight is proposed.*

Keywords: display system, event probability, flight parameters, pictorial element, quantity of visual information which pilot sees simultaneously.

Introduction

During the intensive visual load, the pilot has to organize the control of pilotage parameters (PP) on the frequencies close to minimum required to fulfill flight task based on displayed instrument panel information [1]. Therefore, minimum required frequencies of PP monitoring define a row of numerical characteristics for the structure of pilot visual activity: probability of instrument or information visual display system (VDS); transient probabilities, i.e. probabilities for transfer of pilot view from one instrument to another one and probabilities of two- and three- instrument cycles within the pilot VDS visual field.

Purpose of this study

The purpose of this study assumes identification of analytical dependence for above-mentioned probabilistic characteristics of the pilot visual activity structure versus minimum required characteristics to ensure fulfillment of flight task using pilot addresses to PP.

Task solution

Let`s assume that the pilot fulfills a task on certain flight stage, which requires visual control of N PP and the task is visualized on K instruments. Let us assume that f_i is minimum required frequency in Hz of pilot visual control over i-PP (i = 1,…, N). Average time of pilot view is fixing on visual element (VE) of i-PP we mark via T_{fi}, and average time of pilot view transfer from one VE or instrument to another instrument is as $T_{n.}$. Duration of T_{fi} and $T_{n.}$ is measured in seconds. It is defined that during the application of available PP visualization, the pilot is not able to perceive visually different PP at a time. Therefore the pilot perceives information from different VE in turn [2]. For this setup, we investigate pilot time-dependent capabilities to control identified PP segment.

At the flight stage of duration T seconds, value $n_i = T \times f_i$ and is equal to minimum allowed number of visual pilot addresses to i-PP and $T_{fi} \times n_i = T_{fi} \times T \times f_i$ is equal to total time of pilot view fixing on i-PP during the whole flight stage. Let us call (for specific flight task) minimum probable frequency of pilot visual addresses to n-instrument as frequency $\overline{f}_n$ with number n (n = 1,…, K), for which the pilot is capable to obtain information about visualized PP by exact instrument, and which is required to complete flight task. Thus, value $k_n = T \times \overline{f}_n$ is equal to minimum probable number of pilot view transfers to n-instrument during the whole flight stage, and $T_n \times k_n = T_n \times T \times \overline{f}_n$ is equal to the total time required for the pilot to transfer the view to n-instrument during the whole flight stage. Theoretically, the pilot is able to control identified PP segment, if time is required for PP monitoring and the view transfers is within limits of stage duration, i.e. inequality is fulfilled:

$$\sum_{i=1}^{N} T_{fi} \times T \times f_i + \sum_{n=1}^{K} T_n \times T \times \overline{f}_n \le T,$$

$$\sum_{i=1}^{N} T_{fi} \times f_i + T_n \sum_{n=1}^{K} \overline{f}_n \le 1. \qquad (1)$$

Obtained inequality (1) is called as inequality of pilot time balance for parametric video information.

Fulfillment of inequality is a required condition for probable pilot visual monitoring of N PP segment, when the pilot defines frequencies f_i for monitoring each PP, which are defined by the flight task.

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Formula (1) is used to investigate probability of parametric video information perception by the pilot and disregards visual load on the pilot on indicators panels (failure panel, etc.) in total time-dependent balance. Update of indicator panel status may be fixed by the pilot peripheral view, which is not always controlled by the pilot who is being aware of such updates and recognized by the pilot. Moreover, on intensive flight stages, owing to deficit of time required to control major PP, the pilot, evidently becomes a multi-channel video information reception system in relation to indicator panels.

The left part of the pilot time balance inequality is:

$$\lambda = \sum_{i=1}^{N} T_{fi} \times f_i + T_n \sum_{n=1}^{K} \overline{f}_n \ . \tag{2}$$

This expression bears critical human engineering essence: value λ represents relative visual load of the pilot in relation to parametric video information. Actually, the pilot time balance inequality is equivalent to inequality: $T \times \lambda \leq T$, thus, value λ demonstrates, which part of the flight stage total duration T is consumed by the pilot to control parametric video information.

With λ = 1 the pilot has to consume entire flight stage time for visual control of selected PP segment and has no time for backup, which conforms to the pilot maximum allowed visual load. With λ < 1 visual load of the pilot is less versus of maximum allowed load by λ times and the pilot during entire flight stage duration has extra time of $T(1 - \lambda)$ s. With λ > 1 the pilot is not capable to control all N PP at frequency f_i, and value λ indicates how much the visual load during the control of all PP at frequency f_i exceeds ultimate allowed load. Therefore, value λ is an assessment of pilot visual load versus to maximum probable visual load at frequencies f_i, defined by flight task ($i = 1,\ldots, N$), PP observation and values T_{fi}, T_t specified by VDS quality, i.e. relative visual load of the pilot in relation to parametric information.

During actual instrument flight, time required for the pilot to control instrument panel information is always equal to the duration of flight stage, therefore, with formal approach, relative visual load of the pilot is equal to 1. However, issues related to quality of instrument control by the pilot, which is required by flight task, and relative visual load of the pilot, which is actually equal to the load being defined by flight task, flight conditions and VDS human engineering quality. These issues may be actually solved by experimental & computation method during the comparison of actual frequencies of pilot monitoring PP versus with theoretically required frequencies f_i and computation of value λ as per formula (2).

As we see from formula (2), excess of relative visual load of the pilot over ultimately allowed value 1 is feasible due to the following reasons:

− flight task assigned to the pilot and regulatory documents to complete flights, duty to control excessively large number of PP;

− high frequencies of pilot addresses to PP, which are required to achieve pre-set quality of assigned flight task;

− high duration T_{fi} required to accept video information by the pilot from VE row.

Practical measures to avoid losses of instrument panel video information required to complete flight task and aimed at the reduction of established excessively high relative visual load may include:

− re-distribution of functions among aircraft aircrew members to control instrument panel video information, or introduction of additional aircrew member (in case of high instrument information flow);

− enhanced level of PP automation requiring high frequency of monitoring and management;

− VE improvement (at high T_{fi}) and VDS optimization as a whole;

− training of aircraft aircrew members for reasonable setup of visual activity.

For the purpose of further theoretical studies of the pilot visual activity, let us may an assumption that average duration for acceptance of video information by the pilot from different VE is similar, i.e. $T_{fi} = T_{f.}$ for all $i = 1,\ldots, N$. If this is a case, formula (2) of relative pilot visual load is as follows:

$$\lambda = T_f \sum_{i=1}^{N} f_i + T_n \sum_{n=1}^{K} \overline{f}_n \ . \tag{3}$$

In future, this expression may be used to assess visual load of the pilot for different VDS types.

In formulas (2) and (3) of the pilot relative visual load, the component conforming to n-instrument:

$$\lambda_n = \sum_{i=1}^{N} T_{fi} f_i + T_n \overline{f}_n, \quad n = 1,\ldots, K, \tag{4}$$

where N_n is number of visualized PP by n-instrument,

f_i is minimum required of monitoring frequency for i-PP ($i = 1,\ldots, N_n$);

f_n is information frequency of n-instrument.

Value is equal to share of n-instrument in formulation of entire relative visual load of the pilot and it is evident that:

$$\lambda = \sum_{n=1}^{K} \lambda_n, \quad 0 \le \lambda \le 1.$$

Therefore, aggregation of values λ_n, $n = 1,\ldots, K$, which characterizes distribution of the pilot relative instrument visual load is suitable for investigation and identification of specific values, which entail excessively high visual load of the pilot for certain flight tasks. Review of values allows us to determine, without prejudice, which instrument generates excessively high information flow.

Probability P_n of pilot monitoring of n-instrument on investigated flight stage is determined without consideration of time loss for transfer of pilot view by time ratio, theoretically required for the pilot to control visualized PP by this instrument versus total time required to observe all PP by the pilot. With this determination:

$$P_n = \frac{\sum_{i=1}^{N_n} T_{fi} f_i}{\sum_{i=1}^{N_n} T_n f_n} = \frac{\sum_{i=1}^{N_n} f_i}{\sum_{i=1}^{N_n} f_n}. \quad (5)$$

The last equality in formula (5) is true at $T_{f.i} = T_f$ for all $i = 1,\ldots, N$.

Historical studies of pilot visual fields on VDS, received by technical devices recording position of pilot view fixing point, demonstrated that actual process of VDS scanning by the pilot sufficiently simple is described by Marcovian process of zeroth order [3]. We shall use this result to find theoretical values of transient probabilities and probabilities of two- and three- instrument cycles in the pilot visual field by VDS.

Transient probability P_{AB}, i.e. probability of pilot view transfer from instrument A to instrument B is equal to:

$$P_{AB} = P_A \times P_B . \quad (6)$$

Evidently, $P_{AB} = P_{BA}$.

Probability P_{AB} of two instrument cycles between instrument A and B, i.e. transfer of pilot view from instrument A to instrument B and vice versa from instrument B to instrument A and vice versa, is defined by formula [4]:

$$P_{AB} = \frac{2P_A P_B}{1 - \sum_{i=1}^{K} P_i^2}. \quad (7)$$

Let us find the formula of probability P_{ABC} for three-instrument cycle, i.e. closed visual field of the pilot among the instrument A, B and C. In this case let us assume that random process of pilot view transfer is described by similar Marcovian chain, where spacing represents transfer of view from one VE to another VE.

The event $A \to B \to C \to A$, consisting of pilot view transfer during random number of spacing in Marcovian chain from instrument A to instrument B and finally to instrument C, as well as to instrument A, may be decomposed into the following elementary events in parenthesis: (view fixing on A) and (view hold on A for random number of spacing in the chain) (view transfer from A to B) and (view hold on B for random number of spacing in the chain) and (view transfer from B to C) and (view hold on C for random number of spacing in the chain) and (view transfer from C to A).

Consideration of view holds is extremely important for multi-purpose instruments, which visualize several PP and which are characterized by view transfer from one VE to another VE within one instrument. According to determination of Marcovian chain, events of zeroth order coupled by conjunction “and” are independent and the events consisting of pilot view holds for random (0 to + ∞) number of spacing, are inconsistent. Therefore, according to probability summation and multiplication of probabilities theorems, the probability of event $A \to B \to C \to A$ is equal to:

$$P\left(A \to B \to \overset{\to A}{C} \right) = = P_A \left(\sum_{i=0}^{\infty} P_A^i \right) P_B \left(\sum_{i=0}^{\infty} P_B^i \right) P_C \left(\sum_{i=0}^{\infty} P_C^i \right); \quad (8)$$

$$P_A = \frac{P_A^2 P_B P_C}{(1 - P_A)(1 - P_B)(1 - P_C)}.$$

While formulating this formula, the author used formula of infinitely decreasing progression summation:

$$\sum_{i=0}^{\infty} P_j^i = \frac{1}{1 - P_j} \quad (0 < P_j < 1).$$

The formulae of probable cyclic monitoring of instrument *A*, *B* and *C* starting from instrument *B* or *C* are derived similar to above-mentioned one:

$$P(B \to C \to A \to B) = \frac{P_A P_B^2 P_C}{(1-P_A)(1-P_B)(1-P_C)},$$
$$P(C \to A \to B \to C) = \frac{P_A P_B P_C^2}{(1-P_A)(1-P_B)(1-P_C)}. \quad (9)$$

Therefore, the probability P_{ABC} of three-instrument cycle within the pilot field of vision may be determined by ratio (8) and (9):

$$P_{ABC} = 2P[(A \to B \to C \to A) = = P(B \to C \to A \to B) + + P(C \to A \to B \to C)] = = \frac{2P_A P_B P_C (P_A + P_B + P_C)}{(1-P_A)(1-P_B)(1-P_C)}. \quad (10)$$

Where multiplier 2 considers that cyclic view of instruments *A*, *B*, *C* may be realized in any direction.

Therefore, with assigned flight tasks causing high visual load of the pilot related to instrument information (when $\lambda \approx 1$), minimum required frequencies of pilot visual addresses to PP to ensure pre-set quality of pilotage define theoretically optimal (with reference to criteria to minimize visual loads during reception of all required instrument information by the pilot) numerical characteristics if the pilot visual activity structure, i.e. process of pilot/VDS interaction.

Thus, these theoretical characteristics determined by formulae (4) – (10), are optimal. Actually, human engineering deficiencies in VDS force the pilot to adapt himself and as a result, numerical characteristics of the pilot visual activity structure will differ from theoretically optimal characteristics. As a result, differences between numerical characteristics of actual qualified pilot visual activity structure for certain VDS and theoretically optimal characteristics, without prejudice reflect VDS performance quality and may lay a basis to formulate unbiased methods for assessment of VDS performance qualities. Now, having formula of theoretically optimal characteristics, which allow us to calculate their values with reference to minimum required frequencies of pilot visual addresses to PP, the next and final task for this study of mathematical nature, includes task of formalization to realize comparison of numerical characteristics for actual and theoretically optimal structure of the pilot visual activity. Solution of this task entails determination of system of generalized numerical parameters to assess aircraft VDS performance quality.

Calculated results of theoretical and practical studies obtained on TU-204 flight simulator [5] of empirical probabilities are given in tab. 1 and tab. 2.

Table 1. **Probabilities of pilot monitoring for assemblies of electronic VDS during approach for landing in FD mode**

Indicator segment	Probability of assembly monitoring	
	theoretical	empirical
Gyro horizon assembly (HORIZON):		
HORIZON center, flight director indication, angle of roll	0.609	0.62
Heading assembly	–	0.03
Airspeed assembly	0.106	0.10
Flight altitude assembly	0.285	0.25

Table 2. **Probabilities of cycles in the pilot field of vision on electronic VDS during approach for landing in FD mode**

Visual cycle	Cycle probability	
	theoretical	empirical
HORIZON – airspeed assembly	0.225	0.23
HORIZON – flight altitude assembly	0.604	0.57
Sum of cycle probabilities with support HORIZON assembly	0.829	0.80

The comparison of theoretical and empirical characteristics of information collection from electronic VDS by the pilot given in tab. 1 and tab. 2 has no substantial differences in values. Empirical characteristics of pilot fields of vision on electronic VDS demonstrate that during FD (flight director) approach for landing, pilot takes information about dynamics of heading angle, mostly from indicators of FD mode in the center of gyro horizon assembly and practically omits indication of heading angle. Therefore, theoretical characteristics of information collection process by the pilot from electronic VDS have been calculated without consideration of information reading by the pilot directly from the heading assembly. Similar effect is revealed during the approach for landing using backup instruments of electromechanical VDS.

Conclusions

Represented results allow us to make the following summary about regularities of pilot/VDS interaction during the approach for landing and probabilities to use obtained results for the solution of certain practically important tasks:

1. Basic characteristics of pilot/VDS interaction process are defined by aircraft aerodynamic characteristics and pre-set accuracy of pilotage: flight task, since empirical values practically coincide with theoretical values, which have been calculated and based on minimum frequencies of pilot visual addresses to flight parameters, being crucial for completion of assigned flight task.

2. The structure of pilot visual activity during the approach for landing is determined by availability of basic instrument, visualizing pitch, roll and deviation from glide path, which covers approximately 60% of the pilot visual load associated with instrument information. Fields of pilot vision on VDS mostly consist of two-instrument cycles starting from basic instrument, which shares in fields of pilot vision are determined by theoretical probabilities of pilot monitoring of the other VDS, i.e. actually, by dynamic characteristics of displayed flight parameters.

3. Flight stage being intensive from information point of view, with time constraints for the pilot, theoretical characteristics of pilot/VDS interaction process, which have been calculated with reference to minimum required frequencies of pilot address to flight parameters are optimal by criteria of pilot visual load minimization provided that the pilot adheres to pre-set accuracy of pilotage.

4. Probability to calculate required time for the pilot to perceive instrument information to ensure pre-set accuracy of pilotage with reference to values of minimum required frequencies of pilot visual address to flight parameters, average duration of pilot view fixing on VDS elements and average duration of view transfer across VDS elements allows us to formulate methods for true assessment of pilot visual load on instrument displayed information.

5. Differences in theoretical and empirical values of pilot/VDS interaction indicate specific features of pilot interaction with specific VDS type and, normally, reflect specific human engineering deficiencies of installed VDS forcing the pilot to mitigate such deficiencies by time costs during arrangement of pilot/VDS interaction with theoretically improper characteristics. Therefore, mathematically formalized comparison of theoretical and empirical values for such characteristics may be used to elaborate true methods to assess aircraft VDS human engineering qualities.

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