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THE WAYS FOR IMPROVEMENT OF AGREEMENT BETWEEN IN-FLIGHT AND GROUND-BASED SIMULATION FOR EVALUATION OF HANDLING QUALITIES AND PILOT TRAINING

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Abstract

The problem of disagreement between ground-based and in-flight simulation is solved by the modification of technique for experimental investigations and by the modification of simulator's subsystems. The modified technique consists of a set of procedures including: preliminary definition of Cooper-Harper metrics, usage of special input signal, conduction of precise tracking tasks, evaluation of flying qualities in each channels and total flying qualities, etc.

The influence of visual system (quality of the generated image, stereoscopic effect) are considered too.

1 Introduction

The ground-based simulation is used widely in investigation of different flight control problems. The modern simulator is a complex device consisted of a number of subsystems simulated different modalities (visual, vestibular, kinesthetic) perceived by pilot and used actively in many missions in the piloting process. All these systems are connected with the computer simulated aircraft motion in the real time. The agreement between pilot perception and the results achieved in-flight and ground-based simulation is the purpose in development of simulator subsystem. The aspiration to achieve it led to appearance of sophisticated computer generated visual systems with wide angle of view, moving-based system simulated considerable linear and angular accelerations and the feel force simulation system. Except it the mathematical modeling of aircraft motion and atmosphere turbulence in the range of flight envelope and angles of attack allowed to get the aircraft response close to the flight tests. In spite of this progress in simulator development the experience in their utilization demonstrates the difference between the ground-based and in-flight simulation results.

For example the evaluation of flying qualities conducted on NASA Aimes [1], Wright lab [2], MAI [3] simulators for the same dynamic configurations and conditions demonstrated the considerable difference with flight tests. The agreement of the results might be improved by modification of technique used for ground-based simulation including: the selection of piloting task, instruction for pilot before the experiments, development of manual for usage of the Cooper-Harper scale etc. The current paper is dedicated to some aspects of improvement of agreement by modification of some simulator subsystems and methodology used in conduction of experiments.

2 Modification of technique for experimental investigations

2.1 Definition of the Cooper-Harper metrics.

In experiments on evaluation of flying qualities the Cooper-Harper rating scale is used widely (fig. 1).

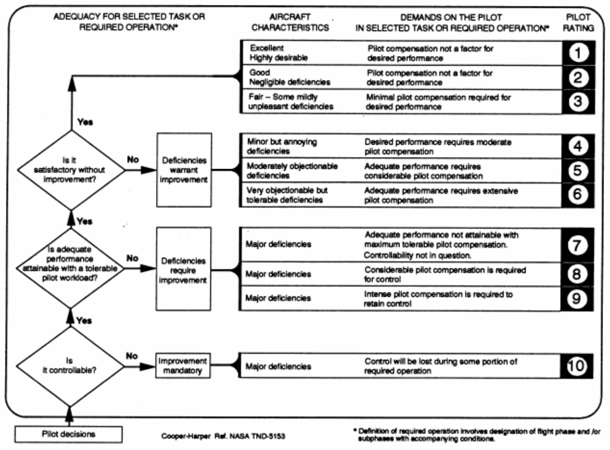


Fig. 1 Cooper-Harper Rating Scale

According to this scale pilot has to compare the achieved task performance and his compensation with the defined preliminary metrics of task performance (“desired” and “adequate”) and metrics of compensation (“is not factor”, “minimal”, “moderate”, “considerable”, etc.). At the same time there are no any recommendations for the definition of these metrics. In some of the researches the task performances were selected. The values of desired and adequate performances for the landing task selected in [1, 2, 3] in ground-based simulation are given in table 1.

Table 1

Task performance	*Shrouder [1]*	*Nguyen [2]*	*MAI [3]*
Desired:			
ΔX, m	± 7.5	±7.5	±7.5
ΔY, m	1.5	-	1.5
V_Z, m/sec	-	1.2	1.5
ΔV, m/sec	± 5	± 5	-
Adequate:			
ΔX, m	± 150	± 150	± 150
ΔY, m	7.5	-	7.5
V_Z, m/sec	-	2.4	2.5
ΔV, m/sec	-5/+10	-5/+10	-

The atmosphere turbulence was not simulated in [2]. It was modeled by Dryden model with mean square error 0.9 m/sec in [1]. Except it in the last research the harmonic gust *(1-cos(ωt))* was added in the simulation of atmosphere disturbance at the altitude *h*=30 m.

The current research was conducted in two stages. In all of them there were investigated the same dynamic configurations (Have PIO data base [4]) as in [1, 2].

Except it the Lahos [5] and Neal Smith [6] configurations were investigated too. At the first stage of investigation the atmosphere turbulence was not included in mathematical modeling. The flying qualities evaluation demonstrated close results of those which are given in [1] and [2]. In particular:

- Lower and higher values of PR in the ranges of the first and the third level of flying qualities correspondingly were achieved at the ground based simulation (fig. 2).

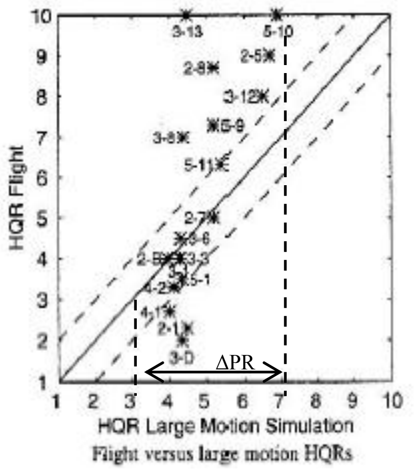


Fig. 2. Agreement of in-flight and ground based investigation

- More narrow interval of flying qualities evaluation (ΔPR) in case of ground based simulation in comparison with in flight investigations.

The interval ΔPR was considered as the difference between maximum and minimum PR given by pilot in experiments with all set of dynamic configurations (see fig. 2). The intervals ΔPR achieved in the mentioned above researches are given on fig. 3.

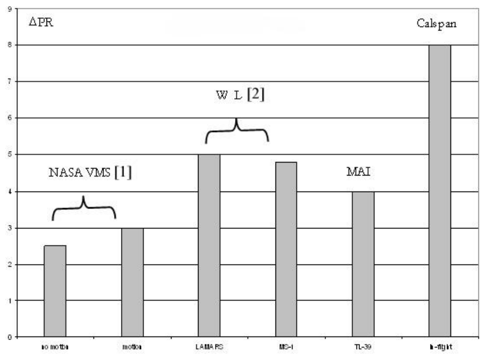


Fig. 3 Interval of pilot ratings in different investigations

At the next stage of research the atmosphere disturbance was simulated by harmonic vertical velocity $W(t) = A_k(1-\cos\omega t)f(t)$. The frequency ω was selected from condition $\omega = 2\omega^*$, where ω^* is the frequency of the resonant peak in the closed-loop system for the case of pitch tracking task. The duration of this signal has to correspond to the period $T = \frac{2\pi}{\omega^*}$ (see fig. 4).

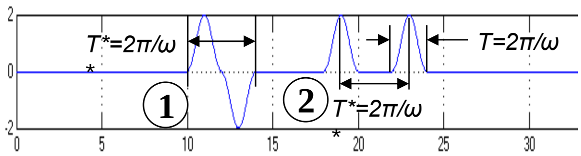


Fig. 4 Special input signal

Two versions of function f(t) were used

$$1)\ f(t) = \begin{cases} +1, t-t_0 \in (0...2\pi/\omega) \\ -1, t-t_0 \in (2\pi/\omega...4\pi/\omega), \quad t_0 = 10s \end{cases}$$

$$2)\ f(t) = \begin{cases} +1, t-t_0 \in (0...2\pi/\omega)\ or\ (4\pi/\omega...6\pi/\omega) \\ 0, t-t_0 \in (2\pi/\omega...4\pi/\omega), \quad t_0 = 16s \end{cases}$$

Utilization of such signal allowed to extent the level of evaluation, ΔPR, from 4 up to 6 and to decrease slightly the variability of flying qualities ratings. In spite of it the estimation of the coordinates (X, Z) and vertical velocities at the touch down point demonstrated the absence of evident correlation between adequate and desired task performances and pilot ratings (fig. 5). For example 65% of landings of configurations belonged to the first level of flying qualities and 88% of configurations belonged to the third level were carried out with accuracy (ΔX, ΔZ) corresponding to the adequate task performance.

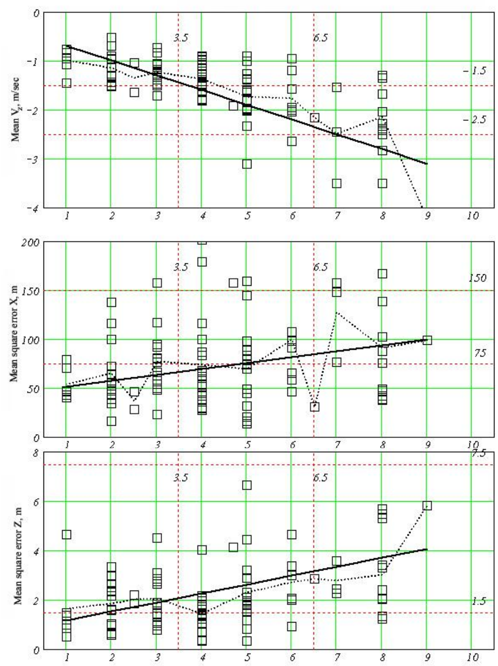


Fig. 5 Variability of the ground-based simulation experimental results

All these results led to the conclusion that the evaluation of flying qualities is defined basically by the aircraft angular dynamics (not the trajectory dynamics) and its corresponding performances. For the test of this suggestion two sets of experiments were conducted. In each of them a pilot carried out the pitch tracking task. In one set the display demonstrated the metrics of the adequate and desired performance except the error signal. In the other set the display demonstrates the error signal only.

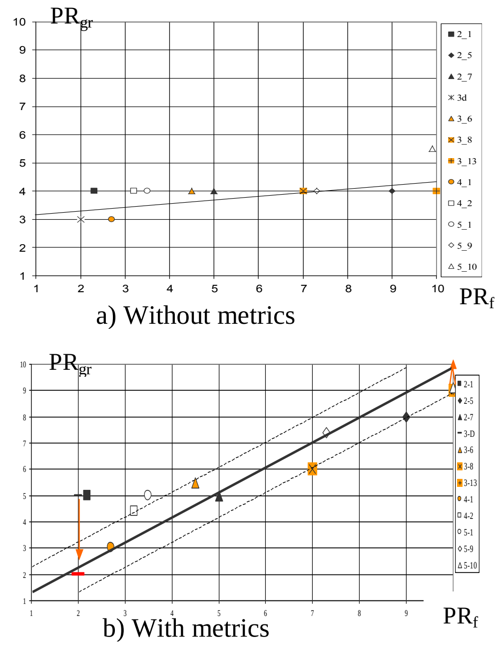
The values of desired and adequate accuracy were selected by use Weber-Fechner law for establishment the dependence between the pilot-rating and value of interval "*d*" in which pilot can hold the "error signal" *e(t)*. It was shown in [7] that

$$PR = 1 + 5.36\ln d \text{ and } d = 4\sigma_e.$$

The polyharmonic signal was used in experimental investigation. Its amplitudes and frequencies were selected according to the technique given in [3] to get agreement with the random signal corresponding to the spectral density

$$S_{ii}(\omega) = \frac{K^2}{(\omega^2 + 0.5^2)^2}, \quad \sigma_i = 4\,sm^2.$$

The values d_{ad} – adequate performance and d_{des} – desired performance were equal to 2.54 sm and 1.75 sm correspondingly. The experiments showed that in case when display demonstrated the adequate and desired metrics the interval of flying qualities evaluation extended up to $\Delta PR_{gr}=6$ (fig. 6) (In the flight test it was equal to 8) This result demonstrated the high importance of influence of aircraft angular dynamics on flying qualities evaluation. The result of such experiments might be more accurate in comparison with the ground based simulation of the landing tasks with the performances defined by the metrics characterizing trajectory motion.



a) Without metrics

b) With metrics

Fig. 6 Agreement of ground-based and in-flight simulation

In many piloting tasks, including the landing, pilot carries out the control in several channels. The increase of the number of channels has to influence on the total pilot rating. It is evident that such total pilot rating PR_m has to be the higher then value of ratings (PR_i) given by pilot in case when he evaluates the flying quality (FQ) in single loops separately.

$$PR_m > \{PR_i\}$$

In the case of dual channel control (pitch and roll channel characterizing by ratings PR_ϑ and PR_φ given by pilot in corresponding single loop tracking tasks) the last equation is the following:

$$PR_{\vartheta\varphi} > \{PR_\vartheta, PR_\varphi\} \qquad (1)$$

The different equations $PR_{\vartheta\varphi} = f(PR_\vartheta, PR_\varphi)$ might be offered.

One of them given in [8] is the following

$$PR_{\vartheta\varphi} = 10 - \frac{1}{8.3}(PR_\vartheta - 10)(PR_\varphi - 10) \qquad (2)$$

The other equation $PR_{\vartheta\varphi}$ combined PR_ϑ and PR_φ and offered by authors is:

$$PR_{\vartheta\varphi} = PR_m - \sqrt{PR_m^2 - PR_\vartheta \cdot PR_\varphi + PR_m}\,, \qquad (3)$$

where $PR_m = \dfrac{PR_\vartheta + PR_\varphi}{2}$.

For evaluation of possibility to use the equation (2) and (3) the results of research [8] were utilized. Here, the number of experiments were conducted for the different parameters of $W_c = \dfrac{\vartheta}{X_{\delta_e}}$ and $W_c = \dfrac{\varphi}{\delta_a}$ (see Table 2).

Table 2

		ROLL	1/T_R (rad/sec)	100	0.5	0.5	4.0
PITCH			τ (sec)	0.0	0.067	0.20	0.067
ζ_{sp} (-)	ω_{sp} (rad/sec)	τ (sec)	Single-Axis PR	1.58	4.0	5.29	2.38
4.526*	11.18	0.0	2.0	2.1		6.5	3.0
0.80	5.0	0.033	2.67	3.5			3.5
0.80	5.0	0.20	3.88			7.0	4.0
0.18*	5.0	0.033	4.0		7.0		
0.18	5.0	0.20	5.8			7.75	7.0

Pitch: $W_c = \dfrac{K_c(s - Z^\alpha)}{s(s^2 + 2\zeta_{sp}\omega_{sp} + \omega_{sp}^2)} e^{-s\tau}$;

Roll: $W_c = \dfrac{K_c}{s(s + \frac{1}{T_R})} e^{-s\tau}$.

These experiments included the single loop pitch or roll control tracking tasks and dual channel control task too. In each experiment the corresponding pilot rating PR_ϑ, PR_φ, $PR_{\vartheta\varphi}$

were fixed (see Table 2). The substitution of PR_ϑ and PR_φ in (2) demonstrated that for several combinations of these ratings the total rating $PR_{\vartheta\varphi}$ is less then one of partial rating in case of equation (fig. 7a, red dots). This result contradicts to mathematical condition (1).

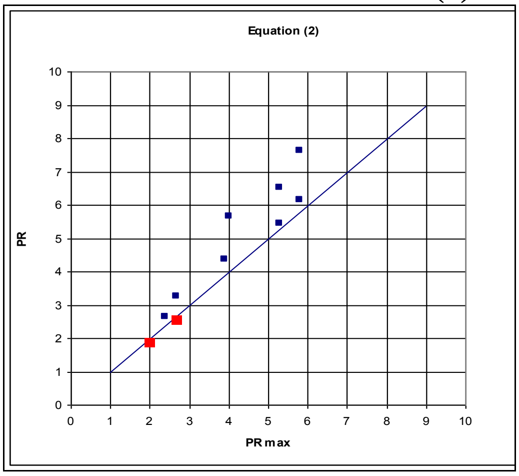


Fig. 7a Test on fulfillment of equation (2).

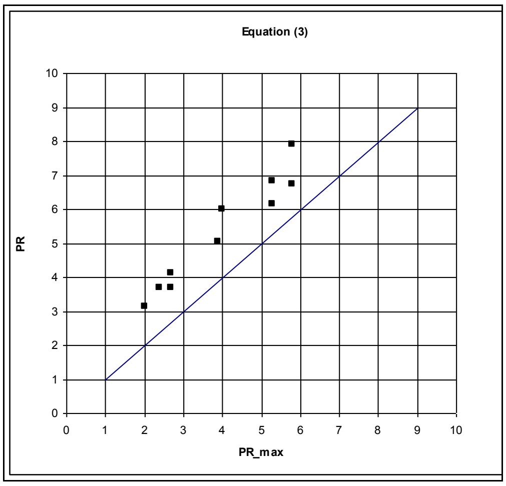


Fig. 7b Test on fulfillment of equation (3).

In case when the PR_ϑ and PR_φ substitute in equation (3) the condition (1) is held (fig. 7b). The equation (3) was used for definition of sensitivity function $\frac{\partial PR_{\vartheta\varphi}}{\partial PR_\vartheta}$ which might be considered as the change of the total pilot rating in case of change of flying qualities in the pitch channel. The equation for this sensitivity function has following from

$$\frac{\partial PR_{\vartheta\varphi}}{\partial PR_\vartheta} = \frac{1}{2}\left[1 + \frac{2(PR_\vartheta - PR_\varphi + 1)}{\sqrt{(PR_\vartheta - PR_\varphi)^2 + 2(PR_\vartheta + PR_\varphi)}}\right]. \quad (4)$$

Small value of this derivative means considerable influence of roll control tracking task on total rating, what does not allow exposing the influence of flying qualities in longitudinal channel on total pilot rating. The increased values of PR_φ decrease $\frac{\partial PR_{\vartheta\varphi}}{\partial PR_\vartheta}$ (fig. 8). For example, in case when $PR_\vartheta = 1$, the increase of PR_φ from 1 to 3 leads to decrease of the derivative in 5 times.

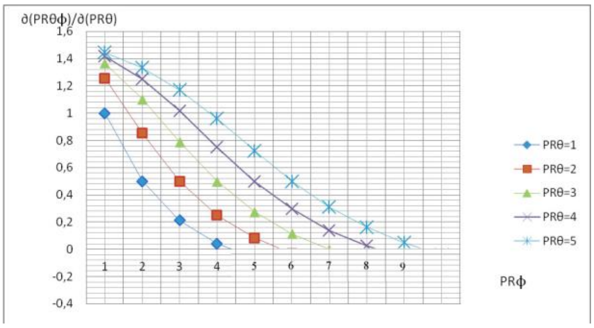
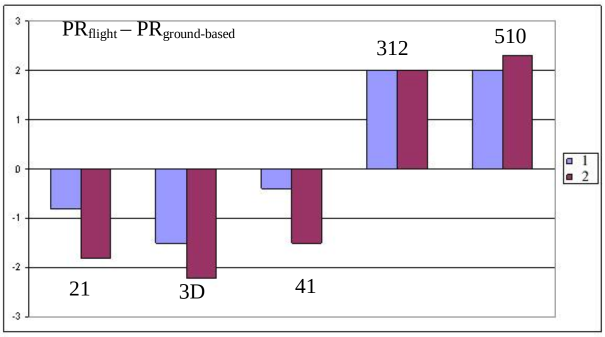


Fig. 8

This result allows to claim that in case when lateral flying qualities will be not the best then the ground-based estimation of longitudinal flying qualities in dual channel control task will has weak sensitivity to the change of flying qualities in longitudinal channel. Such peculiarity has to expose itself at the first level of pilot ratings PR_ϑ mainly.

The third model of equation $PR_{\vartheta\varphi} = f(PR_\vartheta^*, PR_\varphi^*)$, is given in [5] $PR = \max[PR_\vartheta^*, PR_\varphi^*]$. Here PR_ϑ^* and PR_φ^* are the ratings of flying qualities in pitch and bank channel given by pilot in experiments with dual channel control tracking task.

This equation is correct practically for all known experiments [4, 5]. Simultaneous interview of pilot with goal to get the ratings PR_ϑ^*, PR_φ^* and $PR_{\vartheta\varphi}$ allowed to extend the interval ΔPR up to 0.5÷1. The improvement of agreement of ground-based and in-flight evaluation took place for configurations corresponding to the first level (conf. 2.1, 3D, 4.1) (fig. 9). (Here 2.1, 3.D, 4.1, 3.12, 5.10 are the configurations from Have PIO base)



1- with evaluation of FQ in each channel; 2 - without evaluation of FQ in each channel.

Fig. 9 Improvement of agreement of ground-based and in-flight simulation

Thus the ground-based simulation for flying qualities evaluation has to carry out in conditions when:

– The flying qualities in additional channel are close to the best;

– The flying qualities are evaluated in each channels and pilot gives the total rating too;

– The experiments are carried out in conditions of intensive atmosphere turbulence;

– The task performances include the requirements to metrics of angular motion and/or questionnaire contains the questions about dynamic peculiarities of the angular motion.

The integrated effect of the offered technique is the extension of interval of pilot ratings since 4 up to 6.5.

2.2 The influence of the simulator's subsystem fidelity on agreement of in-flight and ground-based simulation

Except the technique for experimental investigation the level of fidelity of simulator's subsystem influences on agreement of ground based and in-flight simulation.

2.2.1 Influence of quality of image generated by computer visual system.

There were carried out two sets of experiments of the landing task differed by the versions of the scenarios. The modified version (fig. 11) differed from the initial one (fig. 10) by more detail drawing of the surface, improved texture and colors, by including the additional 3D elements in scenarios with different heights and located close to the runway.

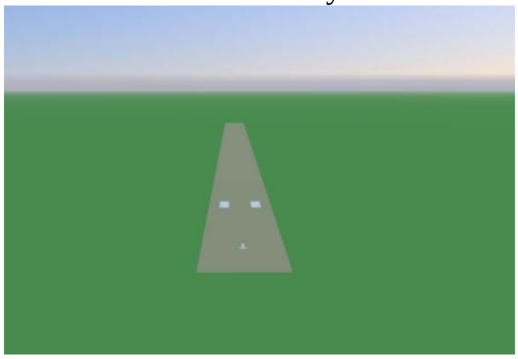


Fig. 10 Initial version of scenario

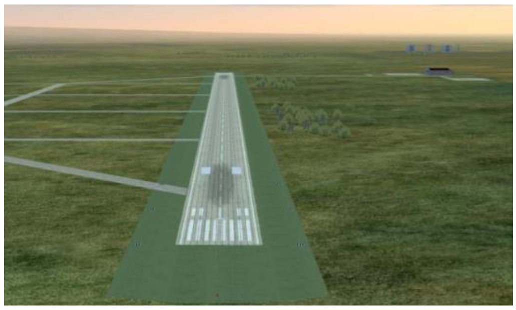


Fig. 11 Final version of scenario

The influence of modification of the generated image demonstrated that it led to extension of interval of evaluation ΔPR up to 0.8 ÷ 1. The improvement of the generated image was accompanied by improvement of the accuracy of landing and considerable decrease of correlation between the variability of the touchdown points with the task performances (decreased and adequate). Practically all landings of dynamic configurations belonging to 1, 2 and 3 flying qualities levels were conducted with accuracy corresponding to the desired task performance.

2.2.2 The influence of moving-based system.

It is not carried out the separate investigation on influence of moving based system in this paper. However the analysis of results given in [2] demonstrate that perception of acceleration leads to increase of the interval ΔPR approximately on 0.5.

2.2.3 The influence of stereoscopic effects

The stereoscopic vision is the human physiological peculiarity allowed to perceive the distance to the observed object. The absence of such effect in case when the usual projector is used decreases the reality and quality of results. Recently the stereoscopic visual system was developed at Moscow aviation institute [9]. It allows to expose the peculiarity of the pilot behavior in refueling task. The stereoscopic effect is exposed highly in this task, because the perceived objects (drogue and boom) are related at the close distance where the stereoscopic effect is highly strong. For the case when the stereoscopic visual system was used in ground-based simulation the pilot realized the different trajectory of the aircraft in comparison with usual project visual system in case when drogue is located aside (fig. 12). In the last case the aircraft moves along the S-form trajectory in the lateral channel (fig. 13).

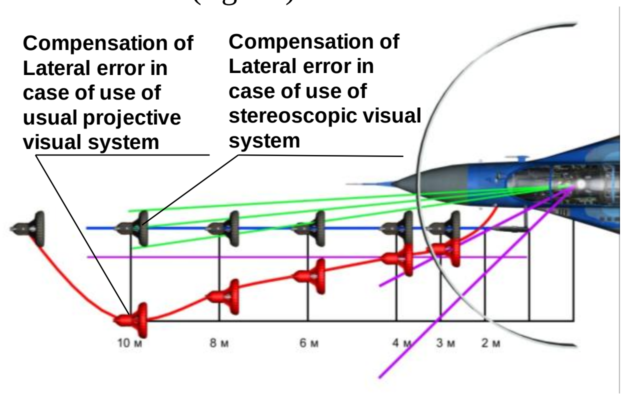


Fig. 12 Aircraft path motion realized for the different visual system

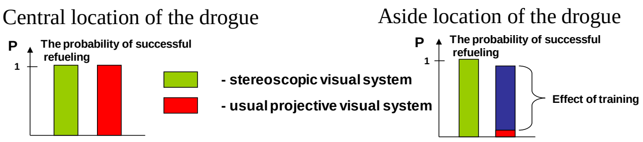


Fig. 13 Probability of the refueling

In case of stereoscopic visual system the accuracy and probability of successful refueling is higher (fig. 13). This effect depends on the level of the training. In case of usual project visual system pilot deflects the stick more actively in lateral channel in comparison with experiments conducted with stereoscopic visual system. (The mean square stick deflection is 30 % higher) These results allowed to give the preliminary conclusion that the use of the project system will be accompanied by slight deterioration of flying qualities evaluation in refueling task in comparison with results of ground-based simulation conducted with the stereoscopic visual system.

In the case of the central location of the drogue the stereoscopic effect is not exposed practically (fig. 12, 13).

Conclusion

The considerable improvement is achieved when the task performances are defined before the ground-based simulation, the experiments are conducted in condition of the intensive atmosphere turbulences. Except the total pilot rating pilot evaluate the flying qualities in each control channel the requirements to the angular motion parameters are included in questionnaire. Besides it the improvement of the qualities of the generated image influences on the agreement too. The total effect of the mentioned above mean allowed to extent the interval of pilot rating since $\Delta PR=4$ up to 6.5. Usage of stereoscopic visual system allowed to approach pilot strategy of action to in-flight strategy in pilot where the observed objects are located close to pilot (in particular refueling task).

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