Modification of the approaches to flying qualities and PIO event prediction.

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Abstract

The following approaches, widely used for the aircraft flying qualities and PIO event prediction are considered:

- Experimental approach based on ground-based simulation;
- Mathematical modeling of pilot-aircraft system;
- Prediction of flying qualities (FQ) and PIO events with the help of the criteria.

Each of the approaches has the deficiencies and limitations in predictions. These issues and ways to address them are considered below.

1. Experimental approach.

Pilot evaluation of flying qualities and PIO event is usually performed in the manual control task when pilot closes the loop (fig.1).

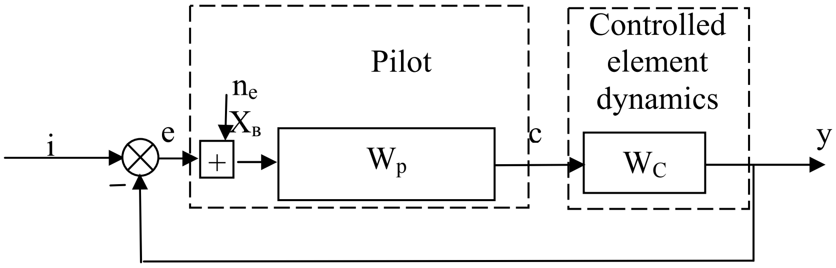


Fig.1 Pilot-aircraft system

The experiments conducted for the different parameters of task variables (controlled element dynamics, input signal, etc) demonstrate the differences in pilot ratings, pilot-aircraft system as well as pilot characteristics. Due to these differences a number of researches was completed to expose the parameters of such characteristics and to define the boundaries of these parameters corresponding to the different flying qualities levels. The ground based simulation completed in [1] allowed to calculate the parameters – the resonant peak of pilot-aircraft system r and pilot compensation parameter Δφ for different linear aircraft dynamic configurations. The rule for estimation of Δφ is given in [2]. As a consequence the "MAI criteria" for flying qualities and PIO prediction has been developed. All the experiments were conducted with the input signal characterizing by the second order filter, variance $\sigma_i^2 = 4[sm^2]$ and desired (d_{des}) and adequate (d_{ad}) task performance equal to 1.75 and 2.54 [sm] correspondingly. The additional experiments were fulfilled for the different precision demand (d) and mean square of the input signal. The precision demand was formulated as the pilot's instruction to keep the perceived error signal e(t) in the specific interval d during the completion of the tracking task.

The influence of parameter "d" on pilot-aircraft system characteristics has been studied for several configurations (HP21, HP510) from Have PIO data base [3]. The results provided in table 1 demonstrate that the decrease of interval d leads to the increase of the resonant peak in the closed loop system and pilot lead compensation.

Table 1 Influence of parameter "d"

	d=4 sm		**d=1 sm**	
	HP21	**HP510**	**HP21**	**HP510**
$\varphi_{p\ \max}$ **[deg]**	**18**	**45**	**54**	**90**
r **[db]**	**0**	**4**	**4**	**9**
σ_e^2 **[sm^2]**	**0.3**	**1.07**	**0.14**	**0.78**
ω_{cp} **, 1/sec**	**1.56**	**1.56**	**3.8**	**2.25**
ω_{BW} **, 1/sec**	**2.74**	**1.85**	**4**	**2.82**

The increase of σ_i caused the similar effects as decrease of variable "d".

The increase of σ_i and decrease of d did not reveal the appearance of the evident resonant peak of the closed-loop system for configuration corresponding to the first level of flying qualities (conf.HP21) (fig.2).

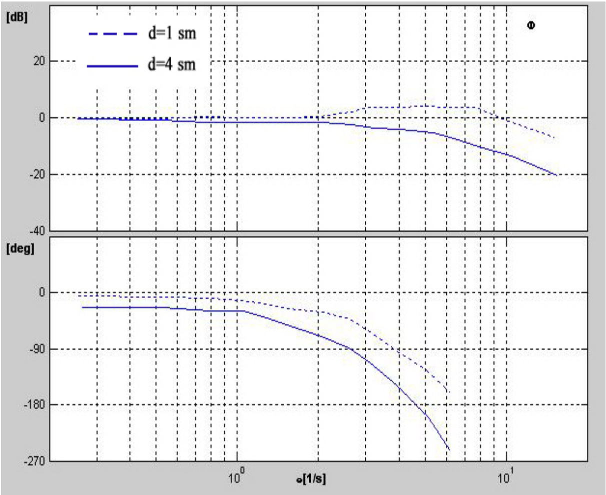


Fig.2. Amplitude and phase characteristics of closed-loop system

The sharp resonant peak (r) in a closed-loop system is typical for configuration corresponding to the third level of flying qualities (conf. HP-510) in experiments with the increased σ_i^2 and small interval "d" (fig. 3).

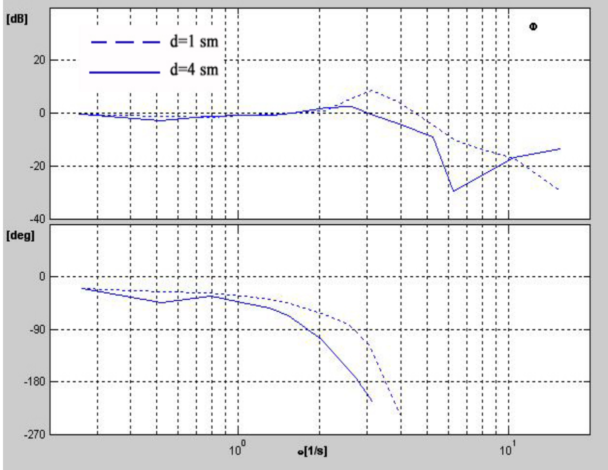


Fig.3. Amplitude and phase characteristics of closed-loop system

The change in these variables caused the change of pilot ratings (PR) too. For example in case of conf. HP510, PR is equal to 8 for d=1[sm] and 4 for d=4[sm]. These results lead to the conclusion that experiments on the flying qualities evaluation have to be conducted with the similar input signals and pilot's instructions on precision demands. Otherwise it is not correct to compare the results of the investigations conducted for the different conditions.

The increase of the resonant peak of closed-loop system r is associated with the decrease of phase margin and increase of the open-loop system amplitude frequency response. Because of the variability of pilot's parameters such effect means the increase of PIO tendency. Thus the studies directed to the exposure of PIO have to be conducted in the conditions of high precision tracking task with the high value of σ_i and small "d".

The experimental studies with the nonlinear controlled element dynamics caused by the actuator rate limit $\dot{\delta}_{\max}$ have demonstrated that the decrease of $\dot{\delta}_{\max}$ causes the deterioration of FQ (increase of PR, variance of error) and the periodical appearance of oscillations with frequency close to 2 [1/sec] in high precision tracking task. At the same time the measurement of equivalent frequency response characteristic of the pilot-aircraft closed-loop system demonstrated the reduction of resonant peak r. The high resonant peak is the feature of PIO tendency for the linear controlled element dynamics. The simultaneous estimation of spectral densities $S_{e_n e_n}(\omega)$ and $S_{e_i e_i}(\omega)$ (where e_n is the component of the error signal correlated with pilot remnant n_e, $e_n = -n_e \dfrac{W_p W_c}{1+W_p W_c}$ and e_i is a part of the error signal correlated with the input signal, $e_i = i\dfrac{1}{1+W_p W_c}$) in these experiments was also conducted. The results are shown in fig.4. It can be observed that for the small values $\dot{\delta}_{\max}$ the spectral density $S_{e_n e_n}$ reaches higher values in comparison with the component $S_{e_i e_i}$ in the specific frequency range close to 2 1/sec. As the oscillations in closed-loop system increase at the same frequency, it is suggested to use the parameter $\rho = \dfrac{S_{e_n e_n}}{S_{e_i e_i}}$ as a criterion characterizing PIO. PIO occurs in case when $\rho > 1$. The criterion might be more than 1 for a linear controlled element dynamics (e.g., in case of very high gain coefficient K_c of the controlled element). In that case the maximum value of ρ is reached at frequency range close to 2 1/sec (fig.5). The recording of the time response for the high gain coefficient (fig.6) has demonstrated that the periodical oscillations with frequency 1.5÷2 [1/s] took place in the closed loop system. The increase of the gain coefficient is accompanied by the increase of the pilot lead compensation and the resonant peak of the closed-loop system shifting at higher frequency.

Thus the PIO tendency and flying qualities can be evaluated for the linear aircraft dynamic with a help of parameters r and Δφ. In case when PIO event takes place it might be confirmed (or predicted) by the parameter (criterion) ρ. The resonant peak of equivalent frequency characteristic of closed-loop system is not reflected the PIO tendency (or event) for the nonlinear controlled element dynamics.

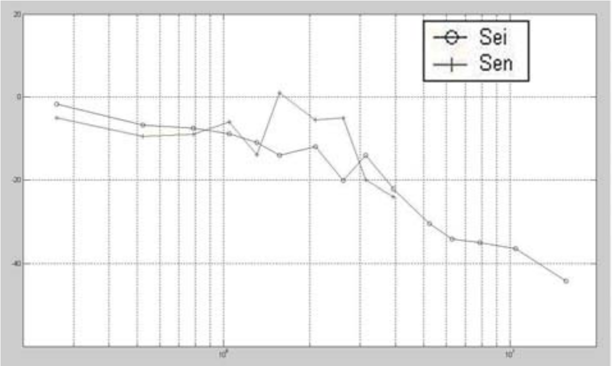


Fig.4. Spectral densities $S_{e_n e_n}$ and $S_{e_i e_i}$

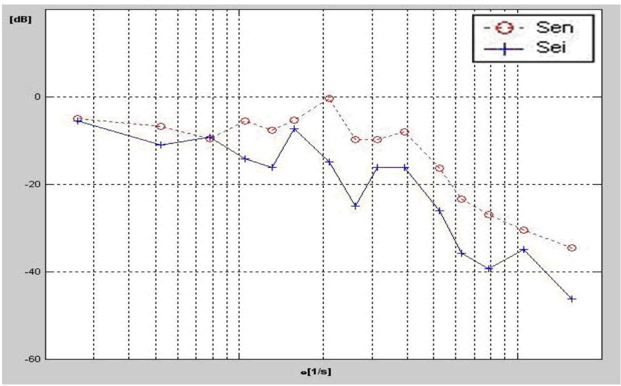


Fig.5. Spectral densities $S_{e_n e_n}$ and $S_{e_i e_i}$

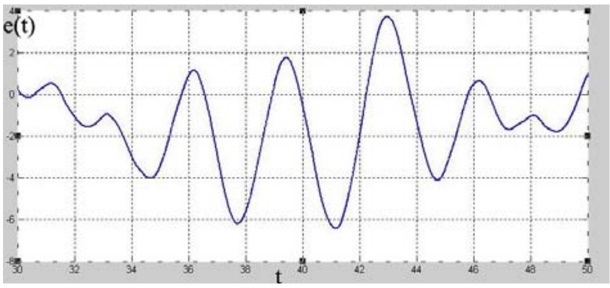
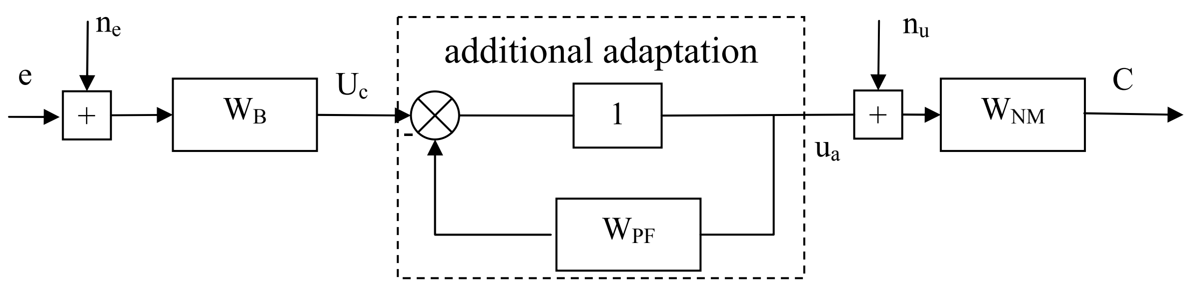


Fig.6. Typical PIO event

2. Mathematical modeling of pilot-aircraft system.

Mathematical modeling of pilot-aircraft system is used widely for the evaluation of some aircraft system parameters (damping ratio, flight control system law, time delay, etc) for FQ and pilot-aircraft system parameters to characterize PIO tendency.

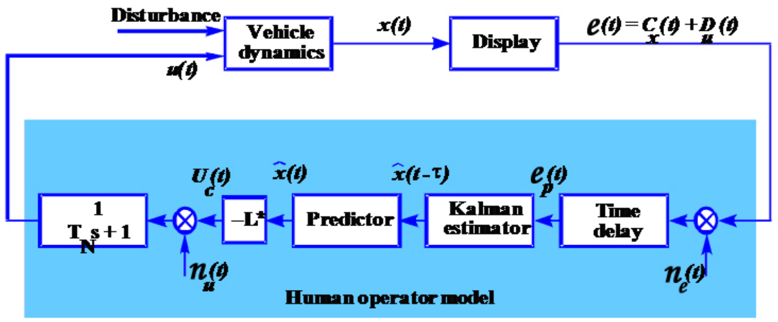
In general two types of pilot models were developed for that purpose: structural model and optimal control model. Many studies have been conducted to modify these models. The latest versions of them developed by authors in [2, 4] are shown in fig.7-8.



$W_{NM} = \frac{1}{s^2+2\xi\omega_{NM}s+\omega_{NM}^2}$ $S_{n_u n_u}=0$ $W_B = K_P \frac{1+T_L j\omega}{1+T_I j\omega} e^{-j\omega\tau}$

$W_{PF} = \frac{K\cdot s^2}{T^2s^2+2Ts+1}$ $S_{n_e n_e}(\omega)=\frac{K^2}{1+T_L^2\omega^2}$ $J=\min(\sigma_e^2)$

Fig.7 Structural model SM



$S_{n_e n_e} = \frac{0.01\sigma_e^2}{K_{n_e}}$; $S_{n_u n_u} = 0.03\sigma_u^2$; $I = \sigma_e^2 + Q_n\sigma_u^2$,

where $Q_u = f(W_c)$ (the values Q_u corresponding different W_c can be found in [1]).

Fig.8 Pilot optimal control model

The detail description of these models can be found in [1, 3]. Despite the fact that the models allow au to get a good correlation with the experiments, they have some deficiencies which do not allow the evaluation of the influence of some variables on pilot-aircraft system. These variables are: controlled element dynamics gain coefficient K_c and the precision demand d (permissible interval “d” of error). The influence of these parameters on pilot-aircraft system characteristics and PIO tendency has been considered above. Because of it the general modifications were developed for the both models.

They are the following:

- The models take into account the existence of the motor noise of the following form

$$S_{nunu} = \rho_u\sigma_u^2 + \sigma_{u_0}^2 ;$$
$$\rho_u = 0.003, \quad \sigma_{u0}^2 = 0.00025[sm^2]$$

- The same form of the cost function was used to select the pilot model parameters “a_i”:

$$J = \min_{a_i}(\sigma_e^2 + Q_u\sigma_u^2);$$

- The same procedure is proposed for a selection of weighting coefficient Q_u. The procedure consists of the following stages:

- Calculation of mean square error $\sigma_e^2 = f(Q_u)$;
- Selection of $d = 4\sigma_e$ (This equation was checked in many experimental investigations);
- Evaluation of Q_u^* for selection of “d”;

- Definition of pilot model and pilot-aircraft system parameters for defined Q_u^*.

The dependences $\sigma_e = f(K_c)$ calculated for several configurations from Have PIO (HP 5-10; HP 2-1) and Lahos (L 2-10) data bases are shown on fig.9.

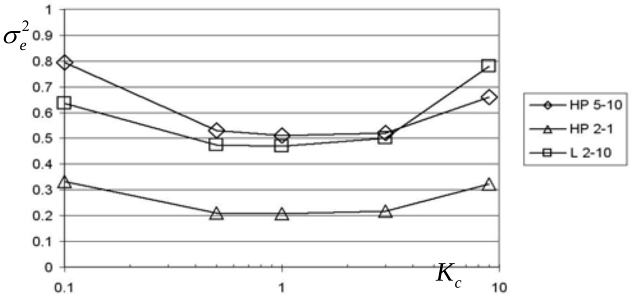


Fig.9. Influence of gain coefficient

The curves have the optimum values and qualitatively agree with the results of experiments. The mathematical modeling demonstrated also that the increase of K_c leads to the increase of resonant peak of closed-loop system and pilot lead compensation. As it was shown above the same results also take place in experiments.

3. Prediction of flying qualities and PIO events with the help of the criteria.

3.1 Problems of using the data bases in the development of FQ.

Development of criteria is the separate problem which is resolved by a mathematical modeling, in-flight or ground-based investigations. The solution of this problem defines the aircraft, pilot-aircraft system parameters and the requirements to them. The augmentation of an aircraft leads to a complex dynamic model of the aircraft + flight control system that is defined by a large number of parameters. This peculiarity demands the studies to be conducted on the development of new criteria based on the requirements of so-called generalized parameters of aircraft or pilot-aircraft system dynamics. These requirements were defined by the use of the results of flight tests where pilot ratings (Cooper-Harper and PIO ratings) had been obtained for the different Have PIO[3], Neal-Smith[5] and Lahos[6] dynamic configurations. As a consequence the corresponding data bases were developed. These data bases are reasonably complete but not completely reliable.

The detailed analysis of pilot ratings demonstrated some shortcomings of experimental studies, in particular:

- The limited number of pilot ratings were obtained for each configuration (in some cases only one rating);
- Considerable deviation of pilot rating for some configurations. In some cases pilot ratings belonged to the different FQ-levels.

Such results influence on the accuracy of the requirement to the parameters and on the FQ prediction as a consequence. For solution of the problem the procedure was developed.

3.2 Procedure for the modification of criteria for FQ prediction.

The procedure consists of two stages:

1. Selection of configurations from the Have PIO, Neal Smith, Lahos data bases characterizing the more reliable in-flight test results.
2. Increase the precision of the boundaries of parameters dividing the levels of flying qualities.

3.2.1 Selection of dynamic configurations for the following modification of criteria.

Configurations have been selected according to the following rules:

- At least two flights had to be completed for FQ evaluation of the considered configuration;
- The ratings PR given by pilot for the considered configuration have to belong to the same FQ level.

According to these rules 38 configurations (9 from the first FQ level, 16 from second level and 13 from the third level) have been selected (see table 2).

Table 2 Selected dynamic configurations

Configuration	Pilot Ratings	Average PR	Level	Configuration	Pilot Ratings	Average PR	Level
LH21	2; 2	2	1	NS3c	4; 3	3,6	2
LH4c	3; 3	3	1	NS3d	4; 4	4	2
NS1b	3,5; 3	3,25	1	NS3e	4; 4	4	2
NS2d	3; 2,5; 2,5	2,7	1	NS4a	5,5; 5	5,25	2
NS8c	3,5; 3	3,25	1	NS7g	5; 6	5,5	2
HP2b	3; 3; 3	3	1	HP36	5; 4	4,5	2
HP21	2; 2; 3	2,3	1	NS1f	8; 8	8	3
HP3d	2; 2	2	1	NS1g	8,5; 8,5	8,5	3
HP41	3; 2; 3	2,7	1	NS2i	8; 8	8	3
NS1a	6; 4; 5	5	2	NS4d	8; 9	8,5	3
LH2a	4; 6	5	2	NS5d	8,5; 9; 9	8,8	3
LH22	4; 4,5	4,25	2	NS5e	8; 8	8	3
LH30	4; 5	4,5	2	HP25	10; 7; 10	9	3
LH1c	4; 4	4	2	HP28	8; 10; 8	8,7	3
LH1-1	4; 4	4	2	HP312	7; 9	8	3
NS2a	4,5; 4	4,25	2	HP313	10; 10	10	3
NS2h	5; 6; 5,5	5,5	2	HP59	7; 8; 7	7,3	3
NS2j	6; 6	6	2	HP510	10; 10	10	3
NS3a	5; 4; 4; 4	4,25	2	LH13	9; 10	9,5	3

Where LH- configurations from the Lahos data base; NS- configurations from the Neal Smith data base; HP- configurations from the Have PIO data base.

3.2.2 Making more precise of the boundaries.

The modified boundaries were defined according to the following procedure:

- To calculate generalized parameters (a_i^*, a_j^*) defining the criterion;
- To plot the points (a_i^*, a_j^*) on the range of parameters with indication of corresponding value PR^*;
- To define FQ boundaries characterizing the best concentration of the points (a_i^*, a_j^*) with corresponding level of FQ;
- To define the percentage of configurations with correctly predicted FQ level (%) for modified and initial version of criterion. The percentage (%) was defined by the following equation:

$$\% = \frac{n\ configurations\ predicted\ correctly}{m\ configurations\ related\ to\ considered\ FQ\ level}.$$

Two types of criteria were studied:

a) The criteria are the requirements for the generalized parameters (time response or frequency response) of effective dynamics;

b) Criteria are the requirements for the generalized parameters of pilot-aircraft system.
Four criteria of the first group were considered:

1. Criterion for FQ prediction as a requirements to the parameters $div = \frac{\Delta q_1}{\Delta q_2}$ and t_1 (effective time delay) of time response q(t) [7] (fig.10)).

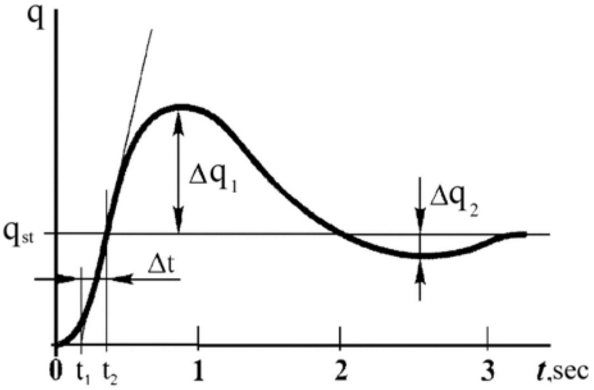


Fig.10. Pitch rate time response

2. Criterion $\tau - \omega_{BW}$ for FQ prediction as a requirements to the effective time delay (τ) and bandwidth (ω_{BW}) of the pitch frequency response characteristics [8] (fig. 11).

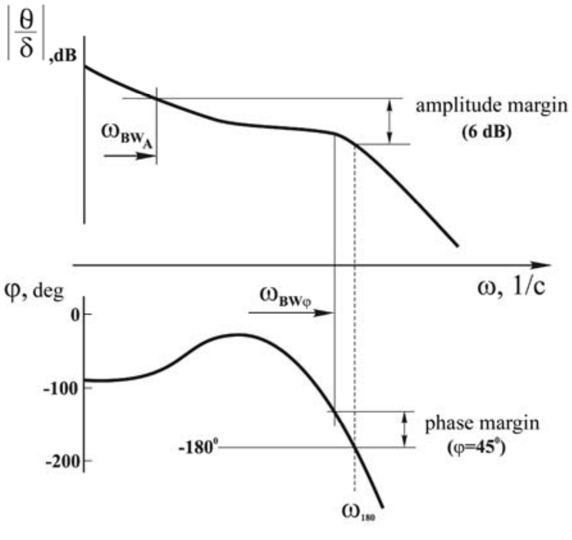


Fig.11. Parameters of $\tau - \omega_{BW}$ criteria

3. Criterion $(\tau - \omega_{BW})^*$ for PIO prediction. This criterion is defined in the terms of the same parameters as the last criteria but have the different boundaries [8] (fig.12).

4. Gibson criterion used for PIO prediction [7]. It is defined in the terms of parameters $APR = \frac{\Delta\varphi}{\omega_{180}}$ and ω_{180} (see fig. 13), where ω_{180} - frequency corresponding to the case when pitch angle phase frequency response characteristics is equal to -180 deg.

$$\Delta\varphi = \Delta\varphi\big|_{\omega=2\omega_{180}} - 180;$$

and $\Delta\varphi\big|_{\omega=2\omega_{180}}$ - pitch angle phase frequency response characteristic at the frequency equal to $2\omega_{180}$.

Two criteria of the second group were considered:

1) MAI criterion [2] (fig.11), using for FQ and PIO prediction and defining in the terms of parameters: r- resonance peak r and $\Delta\varphi$ - pilot compensation parameters. The rules for calculation of the latter are given in [1].

2) Criterion – predicted (calculated) pilot rating $PR_{pred.}$:

$PR_{pred}=\max(PR_{\sigma}\ PR_{\varphi})$, where

PR_{σ} - pilot rating defined by the accuracy of tracking,

PR_{φ} - pilot rating defined by pilot workload. It was obtained that

$$PR_{\sigma} = 3.34(\ln\sigma_e)^2 + 11.02\ln\sigma_e + 4.85,$$

$$PR_{\varphi} = -0.041\Delta\varphi_p + 4.3$$

The parameters of each criteria are given in table 3.

Table 3 Parameters of criteria for selected configurations

	div	tau	w_bw	w180	APR	del_fi_-	del_fi_+	σ_e^2	r
LH21	0,11	0,01	0,50	1,63	10,52	-	13	0.21	1.6
LH4c	0,00	0,02	0,94	3,23	10,96	-	-	-	-
NS1b	0,06	0,03	0,64	1,67	22,55	-19	-	0.16	3.5
NS2d	0,05	0,03	1,01	2,00	21,40	-27	-	0.18	2
NS8c	0,00	0,06	1,00	2,21	44,14	-	-	-	-
HP2b	0,08	0,02	1,04	3,33	11,02	-32	18	0.17	2.3
HP21	0,07	0,01	0,54	1,80	10,55	-18	22.5	0.22	3
HP3d	0,00	0,02	0,90	2,00	13,92	-27	18	0.18	2
HP41	0,03	0,01	0,74	2,25	10,72	-22	9	0.15	3
LH2a	0,12	0,02	1,11	3,40	11,06	-50	30	-	4.4
LH22	0,11	0,08	0,41	0,72	54,36	-	-	-	-
LH30	0,62	0,03	0,35	0,41	23,00	-	-	-	-
LH1c	0,02	0,01	0,22	2,54	10,37	-	-	-	-
LH1-1	0,02	0,01	0,19	1,03	10,27		-	-	-
NS1a	0,10	0,03	0,59	1,43	22,70	-27	19	0.21	4.5
NS2a	0,13	0,03	1,26	2,31	23,60	-	-	0.12	-
NS2h	0,00	0,12	0,45	0,75	83,66	-	30	0.35	3
NS2j	0,00	0,13	0,17	0,61	93,20	-	40	0.49	2.4
NS3a	0,10	0,03	1,80	2,83	22,61	-40	16	0.19	3.5
NS3c	0,00	0,08	0,75	1,50	56,24	-	-	-	-
NS3d	0,00	0,08	0,71	1,30	60,60	-	-	-	-
NS3e	0,00	0,09	0,50	1,17	62,79	-	-	-	-
NS4a	0,40	0,03	0,88	1,35	22,97	-54	10	0.24	4.5
NS7g	0,00	0,07	0,49	1,02	53,71	-	-	-	-
HP36	0,00	0,09	0,74	1,24	62,84	-27	32.5	0.31	5
HP25	0,00	0,19	0,24	0,40	134,71	-	40	0.71	4
HP28	0,07	0,15	0,40	0,62	110,48	-	43.5	0.38	3.5
HP312	0,04	0,28	0,21	0,37	200,84	-	53	0.74	7.85
HP313	0,03	0,24	0,24	0,48	171,03	-	51.5	0.42	4.8
HP59	0,05	0,22	0,26	0,42	160,30	-	51	0.52	5.3
HP510	0,06	0,32	0,20	0,35	229,1295	-	52	0.77	7.94
LH13	0,02	0,16	0,15	0,30	116,97	-	-	-	-
NS1f	0,03	0,20	0,22	0,38	142,80	-	58	0.55	3.4
NS1g	0,00	0,27	0,09	0,26	193,43	-	74	0.75	3
NS2i	0,00	0,18	0,34	0,64	129,94	-	62	0.37	7.7

	div	tau	w_bw	w180	APR	del_fi -	del_fi +	σ_e^2	r
NS4d	0,26	0,16	0,17	0,78	113,63	-	-	-	-
NS5d	0,43	0,17	0,10	0,80	120,74	-	-	-	-
NS5e	2,11	0,19	0,19	0,76	135,24	-	-	-	-

The boundaries of the levels of FQ and ranges for prone and non-prone configurations are given in fig. 12-17.

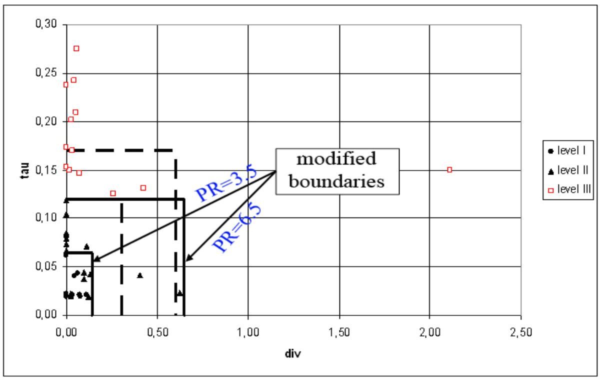


Fig.12. FQ criteria-requirements to time response parameters

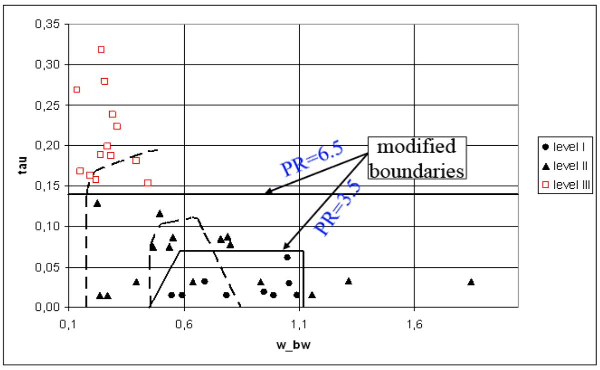


Fig.13. $\tau - \omega_{BW}$ *FQ criteria*

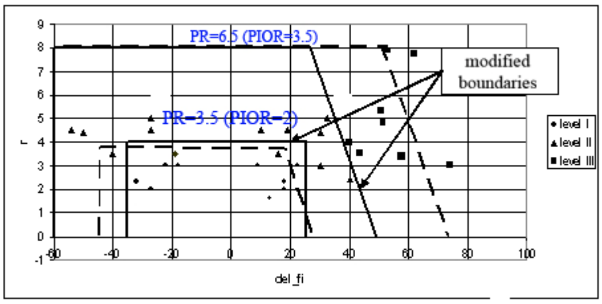


Fig.14. MAI criteria

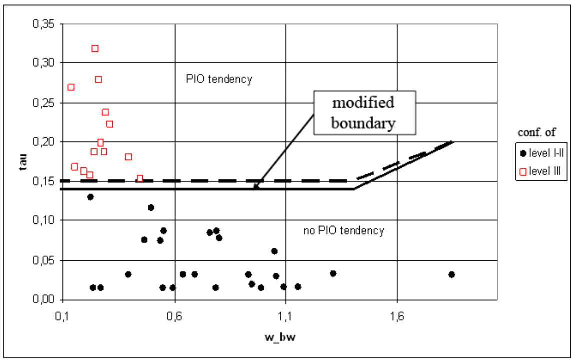


Fig.15. $\tau - \omega_{BW}$ *criteria for prediction of PIO*

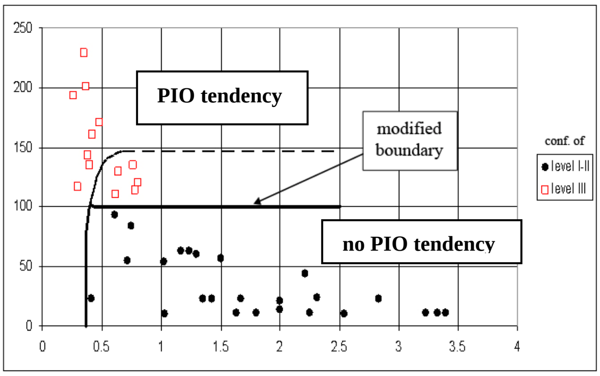


Fig.16. Gibson criteria

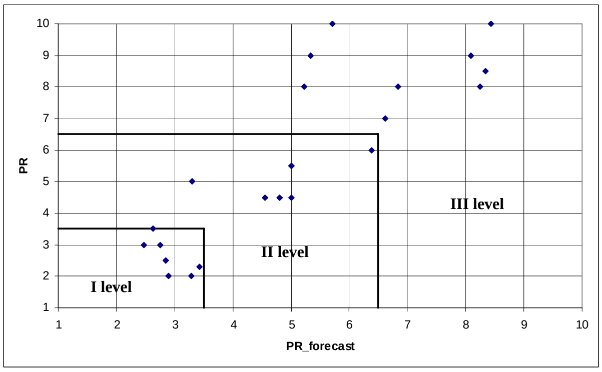


Fig.17. Criteria – predicted (calculated) pilot rating PR_{pred}

The potentialities of these criteria to predict the FQ and PIO events are given in tables 4, 5.

Table 4 Potentialities of criteria for FQ prediction

Criteria	% of configurations predicted correctly	
	Original boundaries	Modified boundaries
Requirements to the parameters of pitch rate response	52,6%	78,9%
$\tau - \omega_{BW_\theta}$	68,4%	94,7%
MAI criteria	34,7%	100%
PR_{pred}	-	82.6%

Table 5 Potentialities of criteria for PIO event prediction

Criteria	% of configurations predicted correctly	
	Original boundaries	Modified boundaries
$(\tau - \omega_{BW_\theta})^*$	97%	100%
Gibson criteria	84,2%	100%

The comparison of the results allowed to make a conclusion that suggested rules for preliminary selection of the data configuration and the following modification of FQ and PIO event criteria led to the improvement of accuracy in the prediction.

References

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