Technique for Flying qualities and PIO prediction

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Keywords: *flying qualities, criteria, PIO, data base, pilot-aircraft system.*

Abstract

A number of approaches are used now for the aircraft flying qualities and PIO event prediction. There are the following:

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

Each of these approaches has the shortcomings and limitations in predictions. Such kind of problems and ways for their solution are considered below.

1. Experimental approach.

At least two problems take place in the ground-based evaluation of the PIO and FQ evaluation:

- Disagreement in the ground-based and in-flight investigations of PIO and FQ evaluation;
- Definition of pilot-aircraft system parameters sensitive to PIO and FQ.

1.1 Disagreement in ground-based and in-flight investigations of PIO and FQ evaluation.

The disagreement between Cooper-Harper ratings corresponding to ground-based and in-flight investigations [1] for “Have PIO” configurations [2] is show on fig.1.

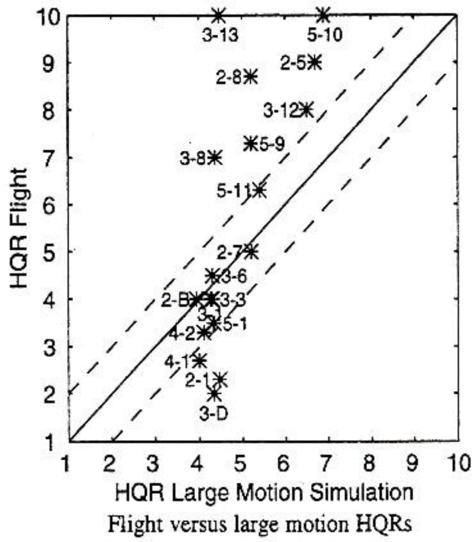

Fig.1. Agreement of in-flight and ground-based investigations

There is seen that the Cooper-Harper ratings (PR) are lower in ground-based simulation in comparison with in-flight evaluation for aircraft with deteriorated flying qualities.

As a consequence the difference between the “worst” (PR_w) and the “best” (PR_b) pilot ratings received in an investigation of the data base configurations $\Delta PR = PR_w - PR_b$, so-called the interval of FQ evaluation [3], is lower (in 2-2.2 times) in ground-based investigations in comparison with in-flight evaluation. Because of the relationship between PIOR (Pilot induced oscillation rating) and PR rating shown in [4]

$$PIOR=0.5PR+0.25$$

the disagreement between FQ evaluation leads to reduction of potentiality to expose

PIO event when the ground-based investigation takes place (to the difficulties in exposition of PIO in ground-based investigations).

Taking it into account the special methodology was developed to improve the agreement between the ground and in-flight simulation. It can be formulated with help of the following rules:

- Preliminary selection of adequate and desired task performances (it has to be done by preliminary set of experiments with configurations corresponding to the specific pilot ratings, for example PR=4, PR=6);
- Creation of stress situation in the process of the piloting task fulfillment (change of runway, considerable atmosphere turbulence, transformation from the instrumental to the visual landing just before the flare);
- Evaluation of FQ in each channel (PR_{υ} and PR_{ψ}) and rating PR_{Σ}.
- Usage of questionnaire, which are differed for each piloting task.
- The use of this technique allows to approach the results of in-flight and ground-based investigations (see fig.2).

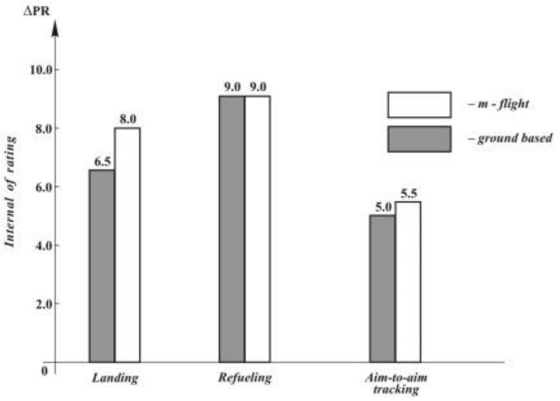

Fig.2. Interval of PR in different piloting tasks

1.2 The definition of pilot-aircraft system parameters sensitive to PIO and FQ.

The number of researches were fulfilled with goal to define the parameters of close-loop pilot-vehicle system correlated with PR or PIOR ratings. There is shown in [5,6] that for the linear aircraft dynamics such parameters are the resonance peak (r), pilot lead compensation parameter $\Delta\varphi_p$. The experimental investigation with the controlled element dynamics taking into account the nonlinearities in flight control system (for example rate limit) demonstrated that the decrease of rate limit causes the deterioration of FQ (increase of PR, variance of error) and leads to the appearance of PIO event in piloting task required the high accuracy. At the same time the decrease of $\dot{\delta}_{\max}$ reduces the resonance peak (r). In many researches high value of (r) is interpreted as obvious fact of PIO. At the same time the measurements of the spectral densities $S_{enen}(\omega)$ and $S_{eiei}(\omega)$ (where e_n – the part of error signal correlated with pilot remnant (n_e) $e_n = -n_e \frac{W_p W_c}{1+W_p W_c}$ and e_i the part of error signal correlated with input signal $e_i = -i \frac{1}{1+W_p W_c}$) demonstrated that decrease of $\dot{\delta}_{\max}$ leads to increase of $S_{enen}(\omega)$ in comparison with $S_{eiei}(\omega)$ in specific frequency range close to $\omega = 2(1/c)$ (fig.3).

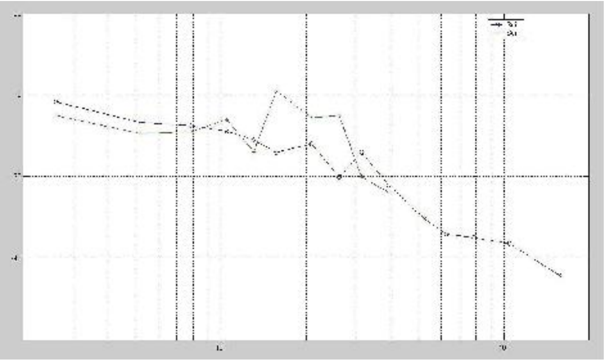

Fig.3. Spectral densities S_{enen} and S_{eiei}

The time response records demonstrated that the PIO with the same frequency of oscillations took place periodically for the decreased $\dot{\delta}_{\max}$ (fig.4). Because of it the parameter $\rho = \frac{S_{enen}}{S_{eiei}}$ was recommended as a parameter characterized PIO. In case when $\rho > 1$, PIO takes place.

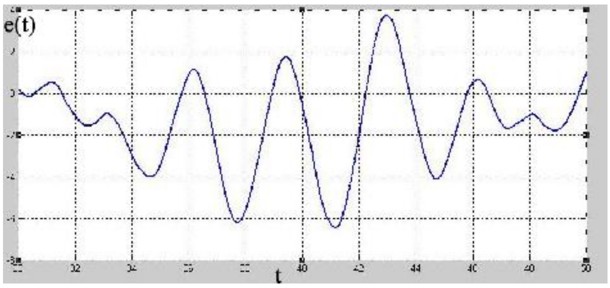

Fig.4. Typical PIO event

2. Mathematical modeling of pilot-aircraft system.

Mathematical modeling of pilot-aircraft system uses widely for evaluation of FQ in the terms of parameters of this system (resonance peak of closed-loop system, pilot lead compensation parameter, mean square error, etc.). Basically two approaches (structural and optimal control) are developed for the modeling. These approaches allows to evaluate this influence of some aircraft dynamic parameters (damping ratio, flight control system law, short period frequency, etc) on FQ and pilot aircraft system parameters characterizing PIO event. Unfortunately anyone of the approaches did not allow to evaluate some of the major parameters which influence on PIO event: controlled element dynamics gain coefficient and requirements to the accuracy (permissible interval "d" of error). It is well-know result that the increase of gain coefficient and decrease of "d" leads to increase of PIO tendency or to appearance of oscillations in angular motion. Because of it the modifications of the both approaches were developed.

The general features for the both approaches are the following:

- Taking into account the motor noise of the following form

$$S_{nunu} = \rho_u \sigma_u^2 + \sigma_0^2$$

$$\rho_u = 0.003, \quad \sigma_{u0}^2 = 0.00025м^2;$$

- The cost function used for selection of pilot model parameters a_i has the form:

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

- The proposed procedure for selection of weighting coefficient Q_u consists of the following stages:

- Calculation of mean square error $\sigma_e = f(Q_u)$;
- Selection of $d = 4\sigma_e$ (This equation was checked in many experimental investigations);
- Evaluation of Q_u^* for selection "d";
- Definition of pilot model and pilot-aircraft system parameters for defined Q_u^*.

The dependence $\sigma_e = f(K_c)$ calculated for several configurations is shown on fig.5.

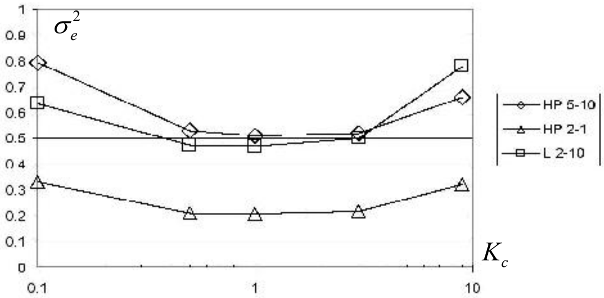

Fig.5. Influence of gain coefficient

The curves have the optimum values and qualitatively have the agreement with the results of experiments. Except it the mathematical modeling demonstrated that increase of K_c leads to the increase of resonance peak of closed-loop system and pilot lead compensation. The same results take place in experiments too.

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

3.1 Problems in use of data bases in development of FQ.

Development of criteria is the separate complex task decided in mathematical modeling, in-flight or ground-based investigations. The solution of the task is the definition of aircraft and pilot-aircraft system parameters and requirements to them. The augmentation of aircraft leads to complexity of dynamic model of the aircraft + flight control system. It requires to the definition of new parameters defined flying qualities. Many new alternative criteria are developed during the last time. The requirements to these parameters are defined by use of results of flight tests. The Cooper-Harper and PIO scales were used in-flight tests of FQ and PIO events in experiments with Have PIO, Neal-Smith and Lahos data bases. These data bases are used in FQ prediction criteria because of they are more full and developed from in-flight tests.

The term “more full” doesn’t means “more reliable”. The detailed analysis of pilot ratings demonstrated some shortcomings of experimental investigations, in particular:

- The limited number of pilot ratings was 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.

These results influence on the boundaries dividing the range of parameters on the different requirements. These shortcomings decrease the accuracy of FQ prediction. Because of it the special 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 Have PIO, Neal Smith[6], Lahos[7] data bases characterizing the more reliable in-flight tests results.
2. Making more precise the boundaries of parameters divided the levels of flying qualities.

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

There were selected the configurations satisfing the following rules:

- At least two flights were fulfilled for FQ evaluation of the considered configuration;
- Pilot ratings obtained for the configurations have to belong to the same FQ level.

According to these rules there were selected 38 configurations (9 from the first FQ level, 16 from second level and 13 from the third level) (see table 1).

Table 1

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

Configuration	Pilot Ratings	Average PR	Level	Configuration	Pilot Ratings	Average PR	Level
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

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

3.2.2 Making more precise of the boundaries was fulfilled according to the following procedure:

- To calculate of generalized parameters (a_i^*, a_j^*) defined the criteria;

- 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 criteria. The percentage (%) was defined by the following equation:

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

Two types of criteria were investigated:

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

b) Criteria are the requirements to generalized parameters of pilot-aircraft system.

Four criteria of the first group were considered:

1. Criteria 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) [2] (fig.6).

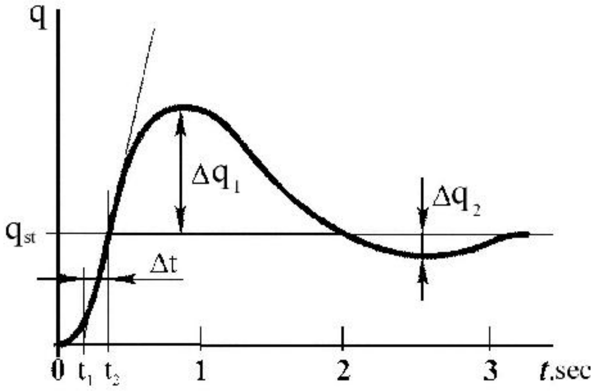

Fig.6. Parameters div and t1

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

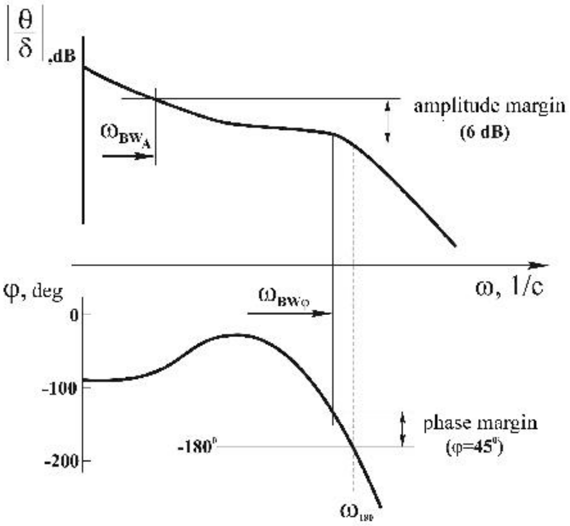

Fig.7. Parameters of $\tau - \omega_{BW}$ criteria

3. Criteria $\tau - \omega_{BW}$ for PIO prediction. This criteria is defined in the terms of the some parameters as the last criteria but have the different boundaries [8] (fig.11).

4. Gibson criteria (fig. 12) used for PIO prediction [8]. It is defined in the terms of parameters $APR = \frac{\Delta\varphi}{\omega_{180}}$ and ω_{180}, where ω_{180} - frequency corresponding to the case when pitch angle phase frequency response characteristics is equal to 180 deg.

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

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

Only one criteria defined in the terms of pilot-aircraft system parameters – MAI criteria [5] (fig.10), was considered. It is used for FQ and PIO prediction and defined in the terms parameters: r-resonance peak and $\Delta\varphi$ - pilot compensation parameters. The last one is defined in [5].

The parameters of each criteria are given in table 2.

Table 2

	div	tau	w_bw	w180	APR	del_fi_-	del_fi_+	r
LH21	0,11	0,01	0,50	1,63	10,52		13	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		3.5
NS2d	0,05	0,03	1,01	2,00	21,40	-27		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	2.3
HP21	0,07	0,01	0,54	1,80	10,55	-18	22.5	3
HP3d	0,00	0,02	0,90	2,00	13,92	-27	18	2
HP41	0,03	0,01	0,74	2,25	10,72	-22	9	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	4.5
NS2a	0,13	0,03	1,26	2,31	23,60			
NS2h	0,00	0,12	0,45	0,75	83,66		30	3
NS2j	0,00	0,13	0,17	0,61	93,20		40	2.4
NS3a	0,10	0,03	1,80	2,83	22,61	-40	16	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	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	5
HP25	0,00	0,19	0,24	0,40	134,71		40	4
HP28	0,07	0,15	0,40	0,62	110,48		43.5	3.5
HP312	0,04	0,28	0,21	0,37	200,84		53	7.85
HP313	0,03	0,24	0,24	0,48	171,03		51.5	4.8
HP59	0,05	0,22	0,26	0,42	160,30		51	5.3
HP510	0,06	0,32	0,20	0,35	229,1295		52	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	3.4
NS1g	0,00	0,27	0,09	0,26	193,43		74	3
NS2i	0,00	0,18	0,34	0,64	129,94		62	7.7

	div	tau	w_bw	w180	APR	del_fi_-	del_fi_+	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-non prone configurations are given in fig.8-12.

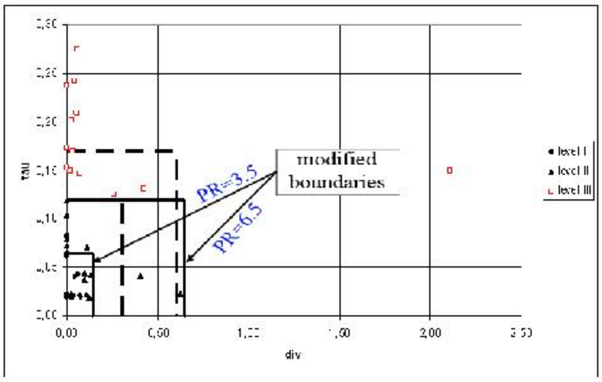

Fig.8. FQ criteria-requirements to time response parameters

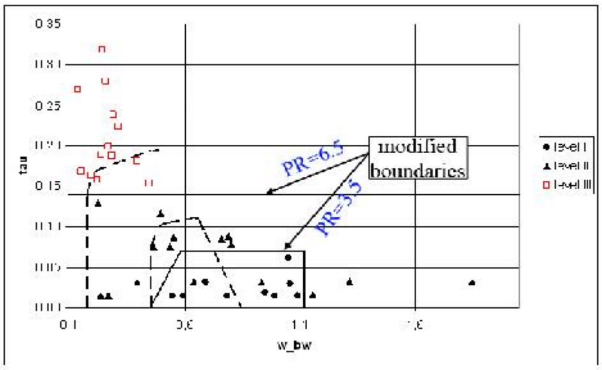

Fig.9. $\tau - \omega_{BW}$ *FQ criteria*

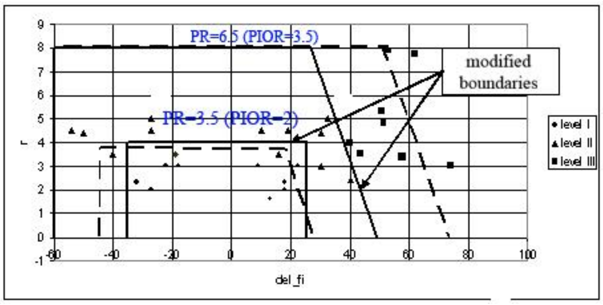

Fig.10. MAI criteria

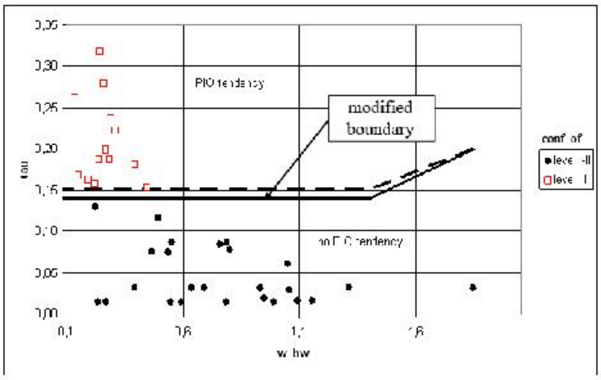

Fig.11. $\tau - \omega_{BW}$ *criteria for prediction of PIO*

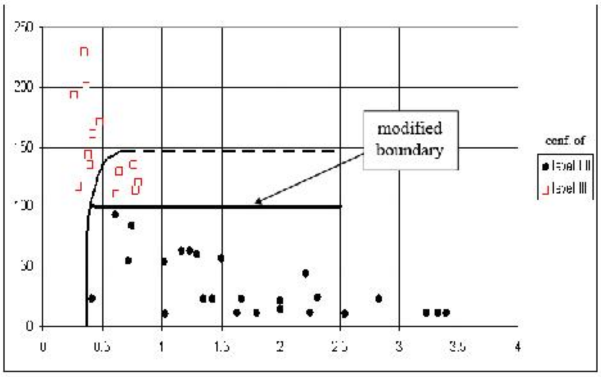

Fig.12. Gibson criteria

The potentialities of these criteria to predict the FQ and PIO events are given in tables 3, 4.

Table 3

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%

Table 4

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

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

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