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A Criterion Based on Closed-loop Pilot-aircraft Systems for Predicting Flying Qualities

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Abstract

During the process of aircraft design, the mathematical model of pilot control behavior characteristics is always used to predict aircraft flying qualities (FQ). This is one of the important methods to avoid pilot-aircraft adverse coupling. In order to study the FQ criterion based on closed-loop pilot-aircraft systems, first, an experimental database is built, which includes 40 aircraft dynamics configurations and the corresponding flight simulation results. Second, the mathematical pilot models with a set of different aircraft configurations are obtained by this experimental database. Then, two FQ criteria, Neal-Smith criterion and Moscow Aviation Institute (MAI) criterion, are analyzed. And the relationship between the FQ level evaluated by actual pilot and the parameters of closed-loop pilot-aircraft systems is studied. Finally, an improved criterion of aircraft FQ is built based on the above two criteria. This new criterion is further used to predict FQ for four new aircraft dynamics configurations, and the prediction results verify its accuracy and practicability.

Keywords: pilot-aircraft system; flying qualities; flight simulation; pilot model; Neal-Smith criterion

1. Introduction

Aircraft flying qualities (FQ) evaluation plays an important role during the process of aircraft design. From the viewpoint of flight dynamics, aircraft FQ refers to whether the pilot can fulfill flight task easily and correctly. If FQ can be predicted at the beginning process of aircraft design, pilot-aircraft adverse coupling will be avoided and flight safety level will be enhanced too [1-4]. Therefore, how to build a criterion to predict FQ is always one of the important tasks for us.

Along with the development of aeronautical techniques, aircraft performance and its automation degree are improved. And new requirements for pilot control behavior are proposed. Due to the fact that the function of complicated pilot-aircraft system is developed, human factors become the main factors to affect aircraft flight safety and aircraft performance[5-8]. Consequently, building a criterion to evaluate modern aircraft FQ mostly depends on closed-loop pilot-aircraft system. Neal-Smith criterion[9] and Moscow Aviation Institute (MAI) criterion [10] belong to this kind of criterion.

Neal-Smith criterion is widely used to evaluate FQ. In this criterion, the accuracy of tracking is met by restricting the maximum droop of amplitude frequency response of closed-loop pilot-aircraft system [9]. This is a boundary requirement. The pilot model with McRuer model form cannot be obtained exclusively by this boundary. So the result of aircraft FQ evaluation is not exclusive too. In the procedure of using MAI criterion, the pilot model can be obtained exclusively with the optimal control model (OCM) of pilot[10]. However this model building does not depend on experimental results but the modern control theory, and the precision of pilot modeling will be lower.

Therefore, when we use the FQ criterion of closed-loop system to evaluate aircraft FQ, how to obtain an exclusive and accurate pilot model becomes important. In order to solve this problem, in this investigation a mathematical model for predicting pilot control behavior characteristics is built based on an experimental database, which has 40 aircraft dynamics configurations. The relationship between the FQ level

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evaluated by actual pilot and the parameters of closed-loop pilot-aircraft systems is studied. Finally, an improved FQ criterion is built based on Neal-Smith criterion and MAI criterion in order to predict FQ corresponding to the pilot rating.

2. Experiments of Closed-loop Pilot-aircraft Systems

2.1. Introduction of experiments

In this investigation, pilot control behavior characteristics in longitudinal pitch tracking task are studied. The closed-loop pilot-aircraft system shown in Fig.1 consists of the blocks pilot, controlled elements dynamics (aircraft and flight control system) and interface (display and manipulator). As a rule, the system with the shown structure works for defined input signals $c(t)$ (commanded task). The pilot perceives a stimulus error signal $e(t)$ by display and an aircraft state output signal $y(t)$ by manipulator. The disturbance $n(t)$ also influences pilot control behavior. The dynamics of controlled element can be mathematically described by the transformation of a control input signal $u(t)$ into an output signal $y(t)$.

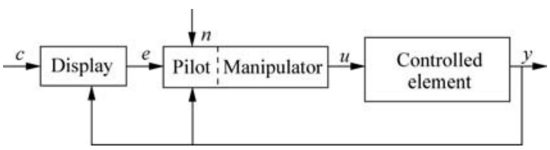

Fig.1 Closed-loop pilot-aircraft system in compensatory tracking task.

The experimental part of work is fulfilled by using the MAI workstation for investigation of manual control task. The compensatory tracking task input signal used in this investigation is pitching angle. It is defined by sum of sine functions based on fifteen single frequencies [11],

$$c(t)=\sum_{k=1}^{15} A(k)\sin(\omega(k)t+\varphi(k)) \tag{1}$$

where A and φ are amplitude and phase of sine functions. Frequency ω in Eq.(1) varies from 0.261 8 rad/s to 15.710 0 rad/s. During the process of experiments pilot controls the elevator $u(t)$ to change the pitching angle of aircraft in order to make output signal $y(t)$ close to input signal $c(t)$, i.e. the control purpose of pilot is to make error signal $e(t)=c(t)-y(t)$ equal to 0.

The pilot must have adequate skill to fulfill the pitch tracking task. And during the process of experiments he must control aircraft actively and efficiently.

2.2. Aircraft dynamics configurations

In order to study aircraft FQ criterion, it is necessary to do adequate experiments with a set of different aircraft dynamics configurations. So, a broad database of configurations is implemented. In the process of FQ criterion's development 40 configurations including 23 Neal-Smith[9] and 17 HAVE PIO[12] configurations are investigated. The pilot rating (PR) of these configurations are varied from 2 to 10 Cooper-Harper scale's metrics. Therefore, it can be used to study criterion of aircraft FQ.

In stead of high order aircraft configuration, the equivalent low order aircraft configuration is always used in the study of FQ criterion. In this investigation, each configuration consists of the control system filter $\dfrac{\delta_{\text{ec}}(s)}{\delta_{\text{es}}(s)}$, the elevator actuator dynamics $\dfrac{\delta_{\text{e}}(s)}{\delta_{\text{ec}}(s)}$ and the aircraft dynamics $\dfrac{\vartheta(s)}{\delta_{\text{e}}(s)}$. Its transfer function has the following form:

$$W_{\text{c}}(s)=\frac{\vartheta(s)}{\delta_{\text{es}}(s)}=\frac{\delta_{\text{ec}}(s)}{\delta_{\text{es}}(s)}\cdot\frac{\delta_{\text{e}}(s)}{\delta_{\text{ec}}(s)}\cdot\frac{\vartheta(s)}{\delta_{\text{e}}(s)} \tag{2}$$

The control system filter consists of first, second and fourth-order linear filters. These filters are of the following form:

$$\frac{\delta_{\text{ec}}(s)}{\delta_{\text{es}}(s)}=\frac{\tau_1 s+1}{\tau_2 s+1} \tag{3}$$

$$\frac{\delta_{\text{ec}}(s)}{\delta_{\text{es}}(s)}=\frac{\omega_1^2}{s^2+2\xi_1\omega_1 s+\omega_1^2} \tag{4}$$

$$\frac{\delta_{\text{ec}}(s)}{\delta_{\text{es}}(s)}=\frac{\omega_1^2}{s^2+2\xi_1\omega_1 s+\omega_1^2}\cdot\frac{\omega_2^2}{s^2+2\xi_2\omega_2 s+\omega_2^2} \tag{5}$$

The elevator actuator dynamics is modeled as a second-order filter:

$$\frac{\delta_{\text{e}}(s)}{\delta_{\text{ec}}(s)}=\frac{\omega_3^2}{s^2+2\xi_3\omega_3 s+\omega_3^2} \tag{6}$$

The longitudinal aircraft transfer function has the following form:

$$\frac{\vartheta(s)}{\delta_{\text{e}}(s)}=\frac{(\tau_{\vartheta 2}s+1)\omega_{\text{sp}}^2}{s(s^2+2\xi_{\text{sp}}\omega_{\text{sp}}s+\omega_{\text{sp}}^2)} \tag{7}$$

Table 1 gives the parameters for the above transfer function. For all configurations, $\xi_3=0.7$.

Table 1 Parameters of HAVE PIO configurations

Configurations	Aircraft dynamics		Control system and actuator dynamics			PR
	$1/\tau_{\vartheta 2}$	$\omega_{\text{sp}}/\xi_{\text{sp}}$	$1/\tau_1$	$1/\tau_2$	ω_3	
HP2B	0.71	2.4/0.64	3.33	10.0	75	4.0
HP21	0.71	2.4/0.64			75	2.3
HP25	0.71	2.4/0.64	∞	1.0	75	9.0
HP3D	0.71	4.1/1.00	20.00	10.0	75	2.0
HP31	0.71	4.1/1.00			75	4.0
HP41	0.71	3.0/0.74			75	2.7
HP42	0.71	3.0/0.74	∞	10.0	75	3.3
HP51	0.71	1.7/0.68			75	3.5
NS1A	1.25	2.2/0.69	0.50	2.0	63	5.0
NS1B	1.25	2.2/0.69	2.00	5.0	63	3.5
NS1C	1.25	2.2/0.69	2.00	5.0	16	4.3
NS1D	1.25	2.2/0.69			75	4.0
NS1E	1.25	2.2/0.69	∞	5.0	63	6.0

Continued

Configu-rations	Aircraft dynamics		Control system and actuator dynamics			PR
	$1/\tau_{\vartheta 2}$	ω_{sp}/ξ_{sp}	$1/\tau_1$	$1/\tau_2$	ω_3	
NS1F	1.25	2.2/0.69	∞	2.0	63	8.0
NS1G	1.25	2.2/0.69	∞	0.5	63	8.5
NS2A	1.25	4.9/0.70	2.00	5.0	63	4.5
NS2B	1.25	4.9/0.70	2.00	5.0	16	5.0
NS2C	1.25	4.9/0.70	5.00	12.0	63	3.0
NS2D	1.25	4.9/0.70			75	2.5
NS2E	1.25	4.9/0.70	∞	12.0	63	4.0
NS2F	1.25	4.9/0.70	∞	5.0	63	3.0
NS2G	1.25	4.9/0.70	∞	5.0	16	7.0
NS2H	1.25	4.9/0.70	∞	2.0	63	5.5
NS2I	1.25	4.9/0.70	∞	2.0	16	8.0
NS2J	1.25	4.9/0.70	∞	0.5	63	6.0
NS3A	1.25	9.7/0.63			75	4.5
NS4A	1.25	5.0/0.28			75	5.5
NS5A	1.25	5.1/0.18			75	6.0
NS6C	2.40	3.4/0.67			75	4.0
NS7C	2.40	7.3/0.73			75	2.8
NS8A	2.40	16.5/0.69			75	4.5

Configu-rations	Aircraft dynamics		Control system and actuator dynamics			PR
	$1/\tau_{\vartheta 2}$	ω_{sp}/ξ_{sp}	ω_1/ξ_1	ω_2/ξ_2	ω_3	
HP27	0.71	2.4/0.64	12/0.70		75	5.0
HP28	0.71	2.4/0.64	9/0.70		75	7.0
HP36	0.71	4.1/1.00	16/0.70		75	4.5
HP38	0.71	4.1/1.00	9/0.70		75	5.7
HP312	0.71	4.1/1.00	2/0.70		75	8.0
HP313	0.71	4.1/1.00	3/0.70		75	8.7
HP59	0.71	1.7/0.68	6/0.70		75	7.3
HP510	0.71	1.7/0.68	4/0.70		75	10.0
HP511	0.71	1.7/0.68	16/.93	16/0.38	75	6.3

The final parameter required for the configuration definition is K_c. This gain is a function of the ratio of elevator to stick deflection. During the ground-based simulation, the pilot to fly a given configuration selects the K_c gearing for that configuration.

For these 40 aircraft dynamics configurations, single loop pitch tracking experiments are fulfilled by pilot in simulator. The results of experiments constitute an experimental database, which is used to study FQ criterion.

3. Pilot Model

3.1. Model of closed-loop pilot-aircraft system

If pilot is replaced by pilot model, the closed-loop pilot-aircraft system shown in Fig.1 can be rewritten as Fig.2, where W_p is transfer function of pilot model and W_c is transfer function of controlled element. In this figure, disturbance condition n is eliminated, because its influence is not studied in this investigation.

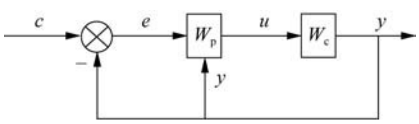

Fig.2 Model of closed-loop pilot-aircraft system in compensatory tracking task.

3.2. Method of pilot modeling

In order to obtain aircraft FQ criterion based on closed-loop pilot-aircraft systems, first of all, the mathematical model for predicting pilot control behavior characteristics must be studied. Ref.[11] gives us a method to build pilot predicting model. This method considers that pilot has different control behavior characteristics with different aircraft dynamics configurations. The results of experiments with different aircraft configurations in closed-loop pilot-aircraft system show that pilot has similar control behavior characteristics for similar aircraft configurations. Therefore, we can adapt the method to predict pilot control behavior, hereinafter introduce it briefly.

(1) To build an experimental database

In this investigation, an experimental database with 40 aircraft dynamics configurations is implemented (see Section 2.2).

(2) To choose similar aircraft configurations

In order to obtain pilot model for predicted aircraft configuration, it is necessary to select two similar configurations for predicted configuration from the database of configurations. This selection is based on Eq.(8), which is used to evaluate similar degree of two configurations,

$$J_i = \sum_{k=1}^{l} [(A_{ci}(\omega_k) - A_{c\,pred}(\omega_k))^2 + \frac{\pi}{180}(\varphi_{ci}(\omega_k) - \varphi_{c\,pred}(\omega_k))^2] \tag{8}$$

where $A_{c\,pred}$ and $\varphi_{c\,pred}$ are amplitude and phase of predicted configuration, $A_{c\,i}$ and $\varphi_{c\,i}$ are amplitude and phase of configuration i in the database of configurations. The range of frequency ω in Eq.(8) can be chosen by concrete instance. The smaller the value of J_i is, the more similar the characteristics between predicted configuration and configuration i are. The value of J_i for each configuration in the database of configurations is calculated. And two configurations, which have the smallest values of J_i, are selected to be similar configurations.

(3) To interpolate the frequency response

According to amplitude and phase frequency response of pilot control behavior for two similar configurations, we can obtain the amplitude and phase frequency response of pilot control behavior for predicted configuration with the method of linear interpolation.

If the similar configurations are called Configuration m and Configuration n, their amplitude and phase are $A_{c\,m}$, $\varphi_{c\,m}$ and $A_{c\,n}$, $\varphi_{c\,n}$. The corresponding amplitude and phase frequency response of pilot control behavior are $A_{p\,m}$, $\varphi_{p\,m}$ and $A_{p\,n}$, $\varphi_{p\,n}$. Therefore, amplitude and phase frequency response of predicted pilot control behavior $A_{p\,pred}$ and $\varphi_{p\,pred}$ can be calculated by interpolating Eqs.(9)-(10) at frequency ω_k.

$$A_{\mathrm{p\,pred}}(\omega_k)=$$
$$A_{\mathrm{p}m}(\omega_k)-\frac{A_{\mathrm{p}n}(\omega_k)-A_{\mathrm{p}m}(\omega_k)}{A_{\mathrm{c}n}(\omega_k)-A_{\mathrm{c}m}(\omega_k)}(A_{\mathrm{c\,pred}}(\omega_k)-A_{\mathrm{c}m}(\omega_k)) \tag{9}$$

$$\varphi_{\mathrm{p\,pred}}(\omega_k)=$$
$$\varphi_{\mathrm{p}m}(\omega_k)-\frac{\varphi_{\mathrm{p}n}(\omega_k)-\varphi_{\mathrm{p}m}(\omega_k)}{\varphi_{\mathrm{c}n}(\omega_k)-\varphi_{\mathrm{c}m}(\omega_k)}(\varphi_{\mathrm{c\,pred}}(\omega_k)-\varphi_{\mathrm{c}m}(\omega_k)) \tag{10}$$

By the way, in order to eliminate influence of configuration gain to parameters of pilot model, it is necessary to standardize amplitude of predicted configuration and similar configurations before interpolation[11].

The method of building pilot model using the experimental database for predicting pilot control behavior characteristics gives us an exclusive and accurate pilot model. This model can be used to predict aircraft FQ.

4. Criterion for Predicting FQ

4.1. FQ rating scale

Currently the accepted aircraft FQ rating scale in the world is Cooper-Harper (C-H) rating scale[13]. According to the aircraft control and the workload of pilot to fulfill various flight tasks, C-H scale uses words to describe aircraft characteristics. And the requirement for pilot in a set task with a numerical rating from 1 to 10 is assigned. C-H scale is subjective pilot evaluation. Detailed description of C-H scale is shown in Ref.[13].

The numerical ratings are often described in terms of FQ "Levels", with Level 1 referring to ratings from 1.0 to 3.5, Level 2 referring to ratings from 3.5 to 6.5 and Level 3 referring to ratings greater than 6.5. These levels are specified in terms of qualitative degrees of suitability in MIL-F-1797[14]:

Satisfactory (Level 1): FQ is clearly adequate for the mission flight phase. Desired performance is achievable with no more than minimal pilot compensation.

Acceptable (Level 2): FQ is adequate to accomplish the mission flight phase, but there is a certain increase in pilot workload or degradation in mission effectiveness, or both exist.

Controllable (Level 3): FQ is such that the aircraft can be controlled in the context of the mission flight phase, even though pilot workload is excessive or mission effectiveness is inadequate, or both.

In this investigation, we study aircraft FQ criterion to predict FQ Level based on Neal-Smith criterion and MAI criterion.

4.2. Neal-Smith criterion

Neal-Smith criterion is originally developed from the observations and results of an in-flight investigation of longitudinal fighter aircraft FQ performing precision pitch tracking [9]. The pilot-aircraft system is shown in Fig.3.

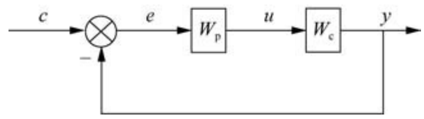

Fig.3 Model of closed-loop pilot-aircraft system for Neal-Smith criterion.

The pilot model W_{p} (McRuer model) is shown in Eq.(11) or Eq.(12)[14],

$$W_{\mathrm{p}}=K_{\mathrm{p}}\mathrm{e}^{-\tau_{\mathrm{p}}s}\frac{T_1s+1}{T_2s+1} \tag{11}$$

$$W_{\mathrm{p}}=K_{\mathrm{p}}\mathrm{e}^{-\tau_{\mathrm{p}}s}\frac{5s+1}{s}\cdot\frac{T_1s+1}{T_2s+1} \tag{12}$$

where τ_{p} is pilot's time delay with fixed value 0.25 s, K_{p} is gain of pilot, and T_1 and T_2 are parameters of pilot lead and lag compensatory. Therefore, the analysis requires the selection of the parameters K_{p}, T_1 and T_2 representing pilot compensation so that the following enumerated performance standards are met: 1)a bandwidth ω_{BW}, defined by a closed-loop phase of −90° (see Table 2); 2)a maximum low frequency droop of −3 dB for $\omega<\omega_{\mathrm{BW}}$, and the type of the compensation leading to a minimum value of resonant peak r. These performance standards are summarized in Fig.4.

Table 2 Requirements of bandwidth in each flight phase

Flight phase	Bandwidth ω_{BW}/(rad·s^{-1})
Category A	3.5
Category B	1.5
Landing	2.5
Other category C	1.5

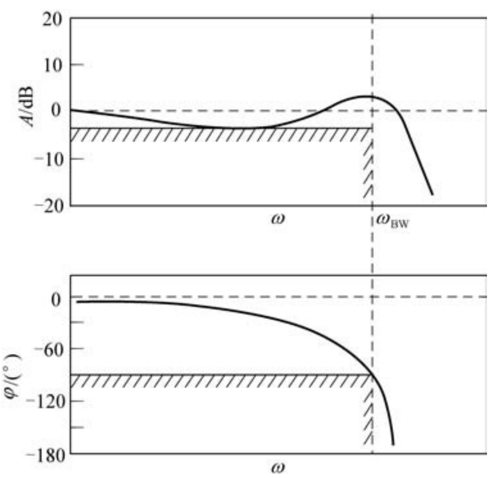

Fig.4 Neal-Smith pilot strategy in tracking.

As shown in Fig.5, Neal-Smith criterion is able to correlate pilot rating with pilot compensation phase $\Delta\varphi_{\mathrm{p}}$ and magnitude of resonance peak of closed-loop pilot-aircraft system r.

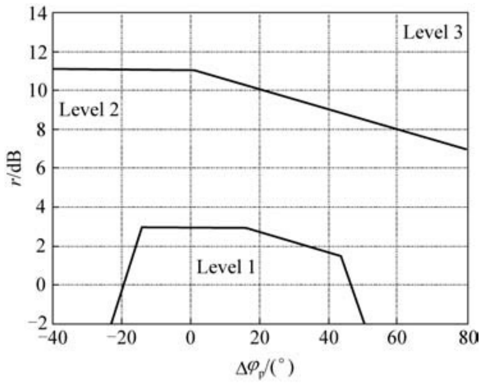

Fig.5 Neal-Smith criterion.

In order to predict aircraft FQ with Neal-Smith criterion, the mathematical model for describing pilot control behavior characteristics in longitudinal pitch tracking task needs to be built. But McRuer pilot model cannot be obtained exclusively by the boundary requirement in Neal-Smith criterion. If the pilot model can be obtained exclusively, the precision for predicting FQ will be enhanced.

4.3. MAI criterion

MAI criterion is based on the work of Neal-Smith criterion. The differences between these two criteria are: ①the method to determine pilot compensatory phase; ②the pilot model.

MAI criterion is defined in terms of resonance peak of closed-loop system r and pilot compensation parameter $\Delta\varphi_p$. Fig.6 gives us Level 1 and Level 2 boundary of MAI criterion (see dashed line) [14-15].

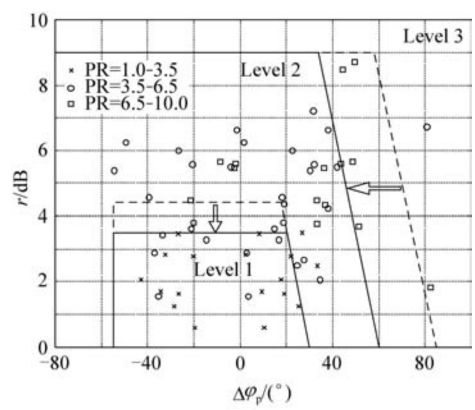

Fig.6 Boundary of MAI criterion and improved criterion.

In Neal-Smith criterion pilot compensation parameter $\Delta\varphi_p$ is determined by the value of pilot phase frequency response at a fixed bandwidth ω_{BW} for different flight phases. Actually the bandwidth is also various in the same flight phase[16-17]. Therefore MAI criterion develops Neal-Smith criterion with new method to obtain pilot compensation parameter. This parameter is defined as the maximum (plus or minus) difference between pilot phase frequency response corresponding to the predicted configuration φ_p and pilot phase frequency response corresponding to the optimal dynamics φ_p^{opt} in wide frequency range, i.e., $\Delta\varphi_p=\varphi_p-\varphi_p^{opt}$. In this investigation, the optimal dynamics is the simplest aircraft controlled element. Its phase frequency response of pilot $\varphi_p^{opt}\approx -57.3\tau\omega$, where $\tau = 0.18$ s[15].

In stead of the simplified model of pilot control behavior (McRuer model) in Neal-Smith procedure, an OCM of pilot is used in MAI criterion and an exclusive pilot model can be obtained.

4.4. An improved criterion of closed-loop pilot-aircraft system

The improved criterion is based significantly on the work of MAI criterion. The difference between these two criteria is the method of pilot modeling. MAI criterion uses the OCM of pilot. The improved criterion uses an experimental database with 40 aircraft dynamics configurations to build mathematical model for predicting pilot control behavior (see Section 3.2). This pilot model can be obtained exclusively. And this modeling depends on the results of experiments, so it can be obtained more accurately.

The closed-loop pilot-aircraft system is comprised of pilot model and predicted aircraft dynamics configuration (see Fig.2). Therefore, resonance peak of closed-loop system r and pilot compensation phase $\Delta\varphi_p$ are obtained. The parameter $\Delta\varphi_p$ is characterized by two values (positive $\Delta\varphi_p^+$ and negative $\Delta\varphi_p^-$). The points ($\Delta\varphi_p^+$, r) and ($\Delta\varphi_p^-$, r) are marked in Fig.6. If these two points belong to different pilot rating levels, the worse result is chosen. For example, for configuration HP42, its ($\Delta\varphi_p^+$, r) = (26.90°, 3.50 dB) and this point belongs to the boundary of Level 2. Its ($\Delta\varphi_p^-$, r) = (−22.84°, 3.50 dB) and this point is in the boundary of Level 1. So the FQ Level of configuration HP42 is Level 2.

The results of such FQ prediction for the database of configurations are shown in Fig.6. The predicted rating levels correspond to the experimental results for 22 configurations from this database. The precision of predicting FQ for Level 1, 2 and 3 are 80%, 68% and 9%. For aircraft configuration with Level 3 the predicting FQ level is the worst. These results show that the boundary of Level 2 of the improved criterion is not fit for the pilot predicting model. In order to improve the results of FQ prediction, the boundaries of Level 1 and Level 2 of MAI criterion are modified (see the real line in Fig.6). The requirement of boundary is stricter. The precision of predicting FQ for Level 2 and 3 is enhanced to 74% and 55% after the boundary is modified.

5. Test for Boundary of Improved FQ Criterion

In order to verify the practicability of the improved aircraft FQ criterion of closed-loop pilot-aircraft system, four new aircraft dynamics configurations are studied:

Configuration A is

$$W_{\mathrm{c}}(s)=\frac{15}{s+15}\cdot\frac{1}{0.2s+1}\cdot\frac{0.5}{0.3s^2+s}$$

Configuration B is

$$W_{\mathrm{c}}(s)=\frac{1}{0.2s+1}\cdot\frac{2s+5}{s^3+2\times1.6\times0.687\,5s^2+1.6^2s}$$

Configuration C is

$$W_{\mathrm{c}}(s)=\frac{15}{s+15}\cdot\frac{0.5}{0.3s^2+s}$$

Configuration D is

$$W_{\mathrm{c}}(s)=\frac{2s+2/1.39}{s^3+2\times1.6\times0.687\,5s^2+1.6^2s}$$

For these four configurations, the levels of FQ evaluated by pilot are from Level 1 to Level 3, therefore this test is a representative one. Table 3 and Fig.7 give us the levels of evaluation by pilot and pilot predicting model.

Table 3 Results of predicting aircraft FQ

Configuration	Level evaluated by pilot	Level predicted by pilot model
A	2	2
B	3	3
C	2	2
D	1	2

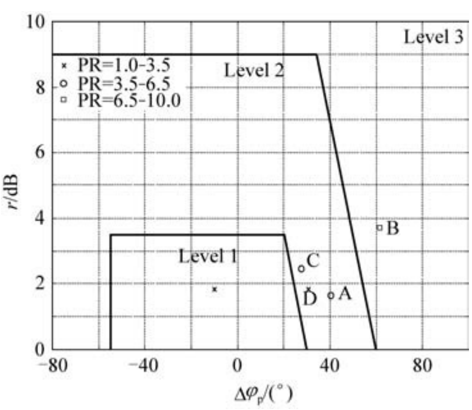

Fig.7 Results of predicting aircraft FQ.

As shown in Table 3, when we predict FQ with the improved criterion, worse level (one level larger than pilot evaluation) is obtained for configuration D only and correct FQ is received for others. Noticeably, the location of the point ($\Delta\varphi_{\mathrm{p}}^{+}$, r) for configuration D is closer to boundary 1 (see Fig.7). These results verify the accuracy and practicability of the improved aircraft FQ criterion.

6. Conclusions

(1) The study is based on experiments. An experimental database, which has 40 aircraft dynamics configurations chosen from HAVE PIO and Neal-Smith configurations, is built. The experiments are fulfilled by using the Moscow Aviation Institute workstation for investigation of manual control task. The models for predicting pilot control behavior characteristics are built based on this experimental database.

(2) An improved FQ criterion of the closed-loop pilot-aircraft system is built based on Neal-Smith criterion and MAI criterion. The FQ levels predicted by pilot model with the improved criterion for four new aircraft dynamics configurations are calculated, and 75% of the predicting results are correct. Therefore we can say that the improved FQ criterion can more accurately predict aircraft FQ.

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