Advancements in Predictions of Flying Qualities, Pilot-Induced Oscillation Tendencies and Flight Safety

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This work discusses the various groups of criteria for the prediction of the flying qualities (FQ) and pilot-induced oscillations (PIO) developed at the Pilot-Vehicle Laboratory (PVL) of the Moscow Aviation Institute (MAI) over the last 25 years. The first criteria group includes requirements for the parameters of highly augmented aircraft. Four of these criteria for FQ and PIO predictions were considered, and the same modification principles were proposed for all the criteria. The second criteria group is based on the requirements for the pilot-aircraft system, and some of the criteria developed at the PVL are discussed. The third criteria group developed at MAI is to calculate the pilot's ratings group. Some of these criteria for single-loop, multichannel, and multimodal piloting tasks were considered. The relationship between the requirements for flight safety and the FQ demonstrates the necessity to modify these requirements for several aircraft classes.

Nomenclature

d = interval excepted as the task performance (see Fig. 5)

d_{des} = desired d

d_{ad} = adequate d

e = error signal

f = parameter defining the distribution for the pilot's attention

F_{es} = pitch control stick force

H = change of altitude at pilot location

K_{n_e} = level of pilot's noise power spectral density

l = distance between pilot's head relative to the X-axis

L = distance between the pilot and drogue

n_y = lateral linear acceleration

$\dot{p}$ = roll rate

p = probability

PR = Cooper-Harper pilot rating

$PR_{i,j}$ = element of PR depending on the specific features ("*i*" or "*j*")

PR^{vis} = element of PR depending on the visual cue

PR^{vest} = element of PR depending on the vestibular cue

r = resonant peak of closed loop system

S_{ii} = power spectral density of input signal

T_{φ} = time constant in transfer function $W_C = \dfrac{\varphi}{\delta_a}$

t_1 = effective delay

Δt_1 = rise time

W_c = controlled element describing function and dynamic configuration

$W_{c\ opt}$ = optimal controlled element describing function

φ = roll angle

$\Delta\varphi^*$ = parameter of Gibson criteria

$\Delta\varphi_{\max}$ = parameter of MAI criteria

θ = pitch angle

δ_e = pilot stick deflection

$\dfrac{\Delta q_1}{\Delta q_2}$ = transient peak ratio

ω_{CL} = pilot-aircraft closed loop system bandwidth

ω_{BW} = pitch attitude bandwidth

τ_p = phase delay, sec

ω_{180} = frequency at which phase of $\frac{\theta}{\delta_e}$ is equal to -180 deg

σ_{n_y} = root mean square of lateral acceleration

$\varphi|_{W_c, W_{c\ opt}}$ = phase angle of W_c or $W_{c\ opt}$

τ = pilot time delay

σ_e = root mean square of error signal *e(t)*

I. Introduction

RESEARCH into the development of criteria to predict flying qualities (FQs) and pilot-induced oscillation (PIO) events and their evaluation using ground-based and in-flight simulations has been performed over at least the last 60 to 70 recent years. Substantial results in this area have been obtained by both American and European researchers.

The pioneering stage of FQ studies that ended in the 1950s was the period when proper selections of the stability margin, stabilizer dimensions and its locations, the dependence of aerodynamic centers on the Mach number, and similarities in airplane configurations guaranteed acceptable handling qualities. Thus, the requirements for FQs were mainly formulated in terms of the requirements for the static stability and gradients of the forces or displacements per unit of the normal load factor. The extension of the flight envelope was accompanied by a considerable decrease in the damping and changes to the parameters of the aircraft time domain response. These requirements include new criteria for the FQs, and the PIO predictions were revised accordingly several times. In the 1970s and 80s, this developmental work was accompanied by intensive research that considered the peculiarities of highly augmented aircraft. Detailed historical analyses of the evolution and revolution of the handling qualities based on the content of these requirements and criteria for FQ and PIO tendency predictions can be found in Ref. [1]. The same criteria have been considered in many other articles such as [2, 3] and works [4, 5].

The results of the developed criteria obtained in the USA and Great Britain evolved into the now well-known Gibson's phase rate criterion, the Neal-Smith criterion, and others. These criteria consider the peculiarities of highly augmented aircraft and are widely used to predict FQs and PIOs. Remarkable results have also been obtained in Russian research centers, including the Moscow Aviation Institute (MAI), which is Russia's major academic and research center. The Pilot-Vehicle Laboratory (PVL) of the MAI has been conducting extensive research into manual control, pilot behavior, flight control, and interface design for more than 40 years.

The main purpose of this paper is to summarize some recent results obtained for the development of criteria to predict FQ and PIO events and determine the relationship between the requirements of the FQ and flight safety.

II. Analysis of Databases

The development of criteria for FQ and PIO tendency predictions is a problem that requires an expertise in databases and the knowledge from in-flight tests.

The databases in question were created in the USA from the 1970s to 90s using a number of in-flight tests. The Neal-Smith [6], LAHOS [7], and Have PIO [8] databases are well-documented examples. These each contain a set of dynamic configurations (W_c) that are implemented using the on-board computer of a T-33A in-flight simulator with the respective pilot's ratings assigned to each configuration following a given flight test. Two scales, namely, a Cooper-Harper rating (PR) and a PIO tendency rating scale [9], were used in the tests.

The criteria used for FQ and PIO predictions indicate that the prediction results often contradict those found through experiments, which may be attributed to database faults associated with the following:

– Limited numbers of flight tests performed for each configuration (in many cases, the number is limited to one test and one rating);

– Considerable variability in a pilot's ratings for some configurations (in some cases, the pilot assigned different PR levels to the same dynamic configurations for different flights).

The averaging of the pilot's rating influences the boundaries that divide the parameters into various ranges that characterize the various FQ levels, which decreases the reliability of the results and calls for more accurate selections of the configurations prior to their use. Therefore, it is proposed that the configurations should be selected from databases that yield more reliable in-flight test results. The "reliable" configurations were selected according to the following rules:

A. Configurations tested at least twice in-flight;

B. Configurations whose FQ ratings belong to the same FQ level or configurations whose FQ ratings belong to different levels but with a difference not exceeding one unit.

Only 5 configurations from all the databases satisfied the latter condition: two of them were assigned PR ratings of 3 and 4 in the two flights (average PR of 3.5), thus belonging to the Level 1 FQ, and three were assigned PR ratings of 6 and 7 in different flights (average PR of 6.5), thus belonging to the Level 2 FQ.

Only 48 configurations from all the databases met these requirements A and B. Eleven configurations belonged to the Level 1 FQ, 21 configurations to the Level 2 FQ, and 16 to the Level 3 FQ, in compliance with the requirements. These 16 configurations were assigned pilot-induced oscillation ratings (PIORs) of more than 3.5.

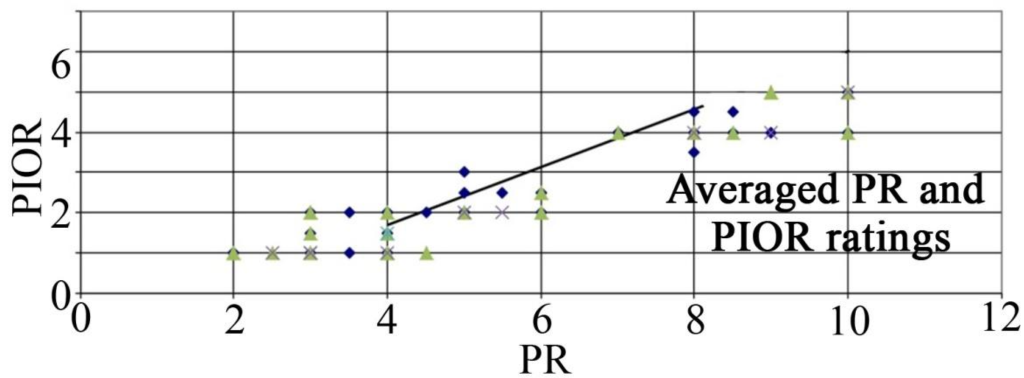

Fig. 1 Correlation between the PR and PIOR ratings.

A comparison between the PR and PIOR for these configurations demonstrates that an increase in the PIOR (Fig. 1) was accompanied by an increase in the PR. This tendency is most noticeable within the PR range of 6-8 where a 2-unit increase in the PR was accompanied by an increase in the PIOR by 2-3 units. For a PR of 6.5 (boundary between the second and the third FQ levels), the PIOR is close to 3.5. Thus, the relationship between the PR and the PIOR within the PR range of 4-8 can be expressed with the following equation [10]

$$PIOR = \frac{1}{3.5}[2.5PR - 4]$$

Within the PR range of 2-6, the PIOR does not change by more than 1.5 units and is always less than 2.5. Considering that a PIOR of 3 is interpreted as a case when a pilot does not induce any oscillations, and a PR of 4 is when such an oscillation takes place, a PIOR of 3.5 might be considered as the boundary where a PIO event occurrence is possible. This conclusion allows the use of the criteria for the FQ prediction (their boundary being between the second and the third levels) as the criteria to set the PIO-prone configurations. Any values that are past the boundary of 6.5 correspond to a case of the PIO-prone configurations.

This conclusion must be used carefully because it is based on the results of in-flight studies of configurations characterized by increased phase delays or small damping ratios. Thus, it cannot be applied to cases when the FQ are unsatisfactory due to a very low controlled element gain coefficient or a very high force per displacement gradient.

III. Modifications of Well-known Criteria

Each dynamic configuration of a database differs from the others through the short period motion parameters or the filter parameters of a transfer function of the controlled element dynamics. It is noted that the pilot evaluation task described in Refs. [7, 8] was for an aircraft landing that included a flare (flight phases related to Category C); however, the tasks described in [6] include several tracking and maneuvering (flight phases related to Category A) activities. As the FQ criteria requirements differ from those for Categories A and C, the Neal-Smith configurations should not be confused with the LAHOS and the Have PIO configurations when modifying the FQ prediction criteria whose boundaries vary between flight mission categories.

The configurations were used to more accurately separate the criteria for the boundaries that divide the parameters into the FQ levels. Several criteria were developed and used for the FQ and PIO tendency predictions. However, only four were selected and considered below to demonstrate the potential of the proposed rules for the preliminary configuration selection. The following criteria were modified:

1. There are three requirements for the criterion regarding the set of pitch rate response parameters in the event of a step input [9, 10]: the transient peak ratio $\frac{\Delta q_1}{\Delta q_2}$; the rise time Δt_1; and the effective time delay t_1. According to Ref. [9], these parameters are calculated from “the two degree of freedom equations of motion (i. e. with speed constrained) for a step controller force and also a step controller deflection.” The initial version of this criterion is given in Table 1.

2. The bandwidth-time delay criterion (“$\omega_{BW} - \tau_p$” criterion) for FQ predictions. The initial versions of the criterion for Categories A and C are shown in Fig. 2. The parameters for this criterion are $\tau_p = -(\varphi|_{2\omega_{180}} + 180)/57.3 \cdot 2\omega_{180}$ and $\omega_{BW} = \max(\omega_{BW_A}, \omega_{BW_\varphi})$ [9].

3. The aircraft bandwidth criterion (“$\omega_{BW} - \tau_p$”) for PIO prediction [11]. These criteria (see Fig. 3) are defined in terms of the same parameters as the criterion considered above, though they have different boundaries.

4. The Gibson's phase rate criterion for the PIO prediction defined in terms of the parameters $APR = \frac{\Delta\varphi}{\omega_{180}}$ and ω_{180} [11], where ω_{180} is a frequency at which the phase frequency response parameter of $\frac{\theta}{F_{es}\ or\ \delta_{es}}$ is -180 deg, and $\Delta\varphi = -\varphi\big|_{\omega=2\omega_{180}} - 180$, where $\varphi\big|_{\omega=2\omega_{180}}$ is the value of the same phase frequency response characteristic at the frequency $2\omega_{180}$. The calculation of these parameters for each configuration and their comparison with the criterion ranges suggests that only the boundary between the L_2 and L_3 ranges of the criterion divides the configurations into prone and non-prone PIO. This result is consistent with the conclusions provided in Ref. [11]. Therefore, the boundary in question was used as the initial version of the Gibson criterion (see Fig. 4).

The modifications to the criterion parameter boundaries that were made by including the maximum number of configurations in the modified ranges were correctly predicted.

The stick force commands (F_{es}) to the flight control system (FCS) were used in the Neal-Smith in-flight investigation [6], which is in contrast to the Have PIO and LAHOS studies where the stick displacement commands of δ_{es} were used. Therefore, the feel system dynamics ($\frac{\delta_{es}}{F_{es}} = \frac{84.5}{(s^2 + 2(0.7)(26)s + (26)^2)}$, in/lb [7, 8]) were only considered when calculating the criterion parameters for the Have PIO and LAHOS configurations.

The controlled element and flight control system dynamics were simulated using the transfer function $W_C = \frac{\theta(s)}{F_{es}(s)\ or\ \delta_{es}(s)} = W_a \frac{K_C(s + 1/\tau_{\theta_2})}{s(s^2 + 2\xi_{sp}\omega_{sp}s + \omega_{sp}^2)}$ where $1/\tau_{\theta_2}$ =0.71 sec^{-1} was the same for the LAHOS and Have PIO configurations. This parameter was equal to 1.25 sec^{-1} or 2.5 sec^{-1} for the Neal-Smith configurations. The parameters ξ_{sp} and ω_{sp} differed for different configurations. The transfer function W_a approximated the FCS dynamics. This was the first order system for the Neal-Smith and LAHOS configurations and the first, second or even forth order filters with variable values for the different Have PIO configurations. See Table 1 and Fig. 2 for the initial and modified requirements for the pitch rate parameters and the boundaries of "$\omega_{BW} - \tau_r$."

Table 1 Requirements for the pitch rate response parameters

Parameter	Level	Requirements			
		Initial		Modified	
		Non-terminal flight	Terminal flight	Non-terminal flight	Terminal flight

		phase		phase		phase		phase	
$\frac{\Delta q_2}{\Delta q_1}$	I	≤ 0.30				No change			
	II	≤ 0.60							
	III	≤ 0.85							
t_1	I	≤ 0.12				≤ 0.072			
	II	≤ 0.17				≤ 0.10		≤ 0.189	
	III	≤ 0.21				≤ 0.21			
Δt		$Min\Delta t$	$Max\Delta t$	$Min\Delta t$	$Max\Delta t$	$Min\Delta t$	$Max\Delta t$	$Min\Delta t$	$Max\Delta t$
	I	$9/V_T$	$500/V_T$	$9/V_T$	$200/V_T$	No change			
	II	$3.2/V_T$	$1600/V_T$	$3.2/V_T$	$645/V_T$				

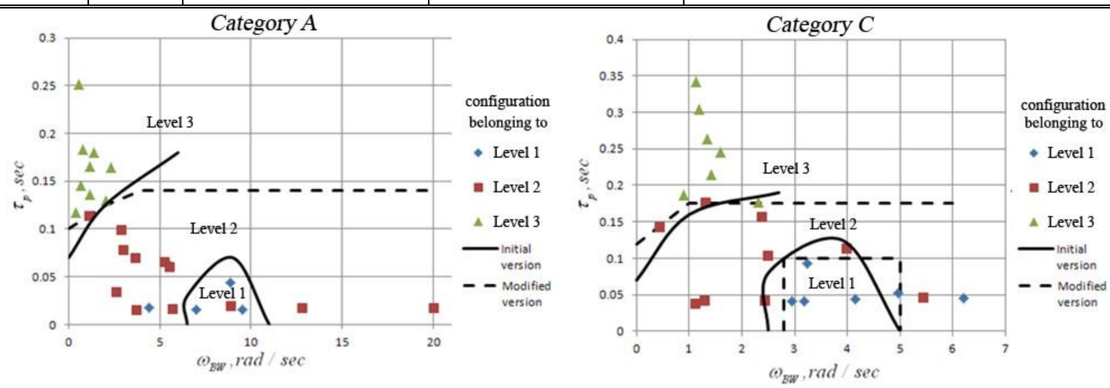

Fig. 2 Bandwidth criterion for the different flight evaluation categories.

Table 2 Potential of the criteria to predict the FQs

	Correct prediction			
Boundaries	Total	Level 1	Level 2	Level 3
1. Requirements for the pitch rate response parameters				
Initial version	32 out of 42 76.2 %	11 out of 11 100 %	10 out of 18 55.6 %	11 out of 13 84.6 %
Modified criteria	38 out of 42 90.5 %	10 out of 11 90.9 %	15 out of 18 83.3 %	13 out of 13 100 %
2. $\omega_{BW} - \tau_r$ for FQ prediction				
Initial version	38 out of 48 79.2 %	7 out of 11 63.6 %	16 out of 21 76.2 %	15 out of 16 93.7 %
Modified criteria	44 out of 48 91.7 %	8 out of 11 72.7 %	20 out of 21 95.3 %	16 out of 16 100 %

The ability of the criteria to correctly predict the FQs are given in Table 2, indicating that the modifications improved the percent of correct predictions. The percent of configurations with correctly predicted FQs was calculated as the ratio between the configurations related to the specific FQ level for the in-flight tests and the total number of in-flight configurations to their respective FQ level. The initial and modified versions of the criteria for PIO predictions are shown in Figs. 3 and 4. Both of the criteria divide the range of parameters into PIO-prone and PIO non-prone configurations. Table 3 shows the percentages and number of configurations that were predicted correctly. It is seen that the modified boundaries improved the potential of the criteria to evaluate the PIO tendency of the considered configuration.

Table 3 Potential of the criteria to predict the PIO

	Correct prediction		
Boundaries	Total	PIO	No PIO
1. $\omega_{BW} - \tau_r$ for PIO prediction			
Initial version	43 out of 48 89.6 %	12 out of 16 87.5 %	29 out of 32 90.6 %
Modified criteria	45 out of 48 93.8 %	16 out of 16 100 %	29 out of 32 90.6 %
2. Phase rate criterion			
Initial version	40 out of 48 83.3 %	10 out of 16 62.5 %	30 out of 32 93.6 %
Modified criteria	45 out of 48 93.8 %	16 out of 16 100 %	29 out of 32 90.6 %

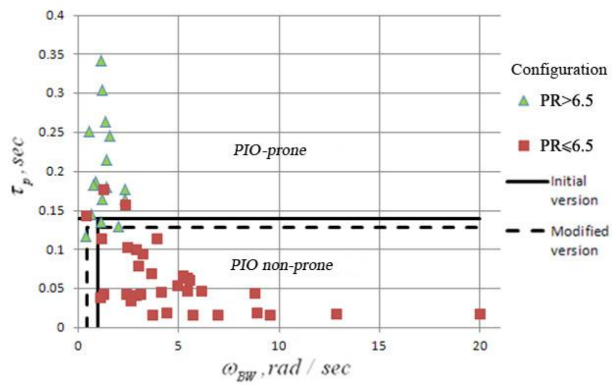

Fig. 3 The $\omega_{BW} - \tau_p$ criterion to evaluate the PIO.

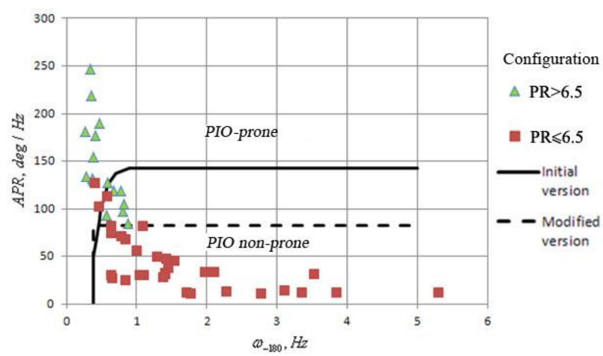

Fig. 4 Phase rate criterion.

The calculation of the criteria parameters without the feel system dynamics gave slightly different boundaries for the parameters, but the percent of correct predictions remained nearly the same:

- 88.1% for the pitch rate parameter criterion;
- 93.3% for the bandwidth criterion for FQ predictions;
- 91.7% for the bandwidth criterion for PIO predictions;
- 93.8% for the Gibson phase rate criterion.

IV. MAI criteria developed from pilot-aircraft system consideration

Two criteria groups were developed at the MAI: one comprises the criteria for the FQ level and PIO tendency predictions (Section A), and the other is the criteria to predict the pilot ratings (Section B).

A. The criteria for the FQ level predictions

1) The MAI criterion (see Fig. 6) to predict the PIO and the FQ during longitudinal motion

This criterion is defined in terms of the resonant peak of the pilot-aircraft closed loop system, r, and the pilot compensation parameter $\Delta\varphi$. The differences between the MAI criterion and the well-known Neal-Smith criterion [6] are the rules that define the parameters $\Delta\varphi$ and r and the boundaries that divide the ranges into parameters related to different FQ levels. Based on the MAI criterion, the parameter $\Delta\varphi$ is found to be the maximum difference between the pilot phase response parameters $\varphi|_{W_c}$ and $\varphi|_{W_{c\,opt}}$ ($\Delta\varphi = \max_{\Delta\omega}(\varphi|_{W_c} - \varphi|_{W_{c\,opt}})$) that correspond to the considered configuration W_c and the optimal controlled element dynamics $W_{c_{opt}}$ within the entire frequency band of the $\Delta\omega$ under consideration.

The optimal controlled element dynamics was defined in Refs. [12, 13] as the dynamics that ensure the simplest type of pilot behavior ($W_p = K_p e^{-j\omega\tau}$) within a broad frequency band and a minimum mean square error σ_e^2 in the compensatory pilot-aircraft system. The equations for $W_{c\,opt}$ provided in Refs. [12, 13] are functions of the power spectral density input parameters n and ω_i ($S_{ii} = \dfrac{k^2}{(\omega^2+\omega_i^2)^n}$), and the pilot limitation parameters (the pilot time delay τ and the level of the pilot noise power spectral density K_{n_e}). For the case of $\omega_i = 0.5$ and $n = 2$, $\tau \cong 0.18 - 0.2$ sec and pilot phase frequency response $\varphi|_{W_{C_{opt}}} = -57.3(0.18-0.2)\omega$ deg. The parameters $\varphi|_{W_c}$ and r are defined in either experimental investigations or mathematical modeling of the pilot-aircraft compensatory system for pitch tracking tasks given the input signal $i(t)$ that characterizes the same power spectral density $S_{ii}(\omega) = \dfrac{k^2}{(\omega^2+0{,}5^2)^2}$ for $\sigma_i^2 = 4\,sm^2$. It is shown in Ref. [12] that this spectral density corresponds to the signal used in Refs. [6, 7] to study the in-flight FQs.

The parameters for the pilot-aircraft system $\Delta\varphi$ and r were obtained in Ref. [13] based on ground-based tests performed at one of the MAI simulators, where a pilot performed pitch tracking tasks funder various dynamic configurations $W_C(j\omega)$. The selection for the desired and adequate performances was based on the assumption that the pilot's rating PR_i is determined by the performance d_i according to the Weber-Fechner law

$$PR_i = B + A \ln d_i \qquad (1)$$

The tracking error *d* level was accepted as the performance, which is an interval within which the error signals continue to move around throughout an experiment (see Fig. 5).

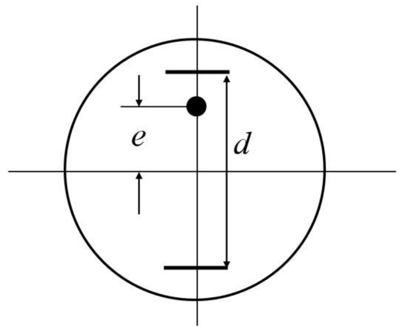

Fig. 5 Display for the FQ evaluation in tracking tasks.

It has been demonstrated that $d = 2\sigma_e$ [10] (where σ_e is the root of mean square error) with a probability of 95%. Finding the constants A and B in Eq. (1) implies knowledge of the two pilot's ratings obtained from in-flight tests with two dissimilar configurations and their respective *d* values found from experiments. It was demonstrated in Ref. [13] that the relationship between the d_{des} and d_{ad} performances is given as

$$\left[\frac{d_{des}}{d_{ad}}\right]^{\frac{5}{3}} = \frac{d_{ad}}{d_{opt}}$$

where d_{opt} is achieved internally in the experiments with optimal control dynamics. For the considered input signal, d_{opt}=1 sm, d_{des}=1,75 sm, and d_{ad}=2,54 sm .

Experiments using 66 different Neal-Smith, Have PIO, and LAHOS configurations were conducted under the above conditions. The resulting MAI criterion and the initial version [12] are shown in Fig. 6. The efficiency of the proposed rules to select the configurations and the subsequent modifications of the criteria was investigated for only the 22 configurations that met the rules in question. The modification of the boundaries increased the number and percent of correctly predicted configurations to 20 and 90.9%, respectively. As the boundary between Levels II and III of the FQ correspond to a PR of 6.5 with an associated PIOR of 3.5, this boundary divides of the configurations into the PIO prone and the PIO non-prone configurations. Thus, the modified criterion might also be considered as the criterion for PIO tendency prediction (see Fig. 6 and Table 4 for details).

Table 4 MAI criteria for FQ and PIO predictions

1. r and $\Delta\varphi$ from experiments

Boundaries	Total	Level 1	Level 2	Level 3
Initial version	17 out of 22 77.2%	5 out of 5 100%	6 out of 8 75%	6 out of 9 66.7%
Modified criteria	20 out of 22 90.9%	4 out of 5 80%	8 out of 8 100%	8 out of 9 88.9%
2. r and $\Delta\varphi$ from optimal pilot model				
Boundaries	Total	Level 1	Level 2	Level 3
Initial version	16 out of 22 72.2%	4 out of 5 80%	7 out of 8 87.5%	5 out of 9 55.6%
Modified criteria	19 out of 22 86.4%	4 out of 5 80%	7 out of 8 87.5%	8 out of 9 88.9%

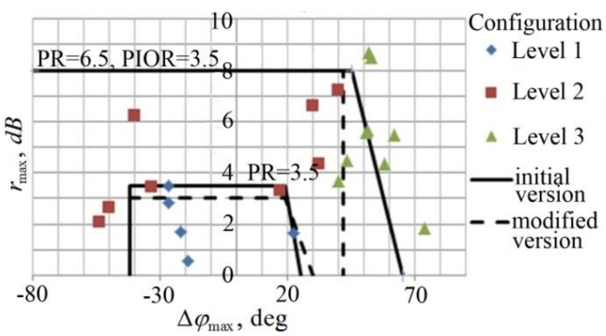

Fig. 6 Modified MAI criterion (r and $\Delta\varphi$) with boundaries found from experiments.

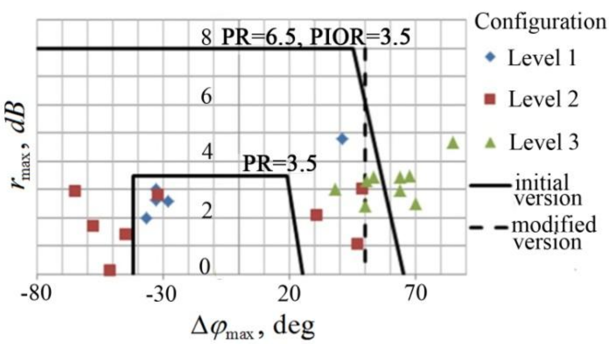

Fig. 7 Modified MAI criterion (r and $\Delta\varphi$) found from the optimal pilot model.

The parameters $\Delta\varphi$ and r can be defined from mathematical modeling, which was done using the pilot optimal model [12] and pilot composite model [14]. The modeling of the pilot-aircraft system with the pilot optimal model was performed for the same 22 configurations where the $\Delta\varphi$ and r were calculated for each configuration. Comparisons of the results with the initial boundaries of the MAI criterion demonstrated that only 16 configurations (72.2%) and 5 PIO-prone configurations (55.6%) were correctly predicted. Therefore, modifications to the criterion's boundaries were offered. The modified boundaries (Fig. 7) increased the percentage of correct FQ and PIO predictions to 90.9% and 88.9%, respectively (see Table 4).

The parameters r and $\Delta\varphi$ were calculated for 20 configurations using the so-called composite model based on a neural network approach [14]. These calculations provided modified boundaries, as shown in Fig. 8. It was demonstrated in [15] that modified boundaries increased the number of successful predictions to 19 of the 20 configurations. Different MAI criterion boundaries are given by the various techniques used to define the parameters $\Delta\varphi$ and r.

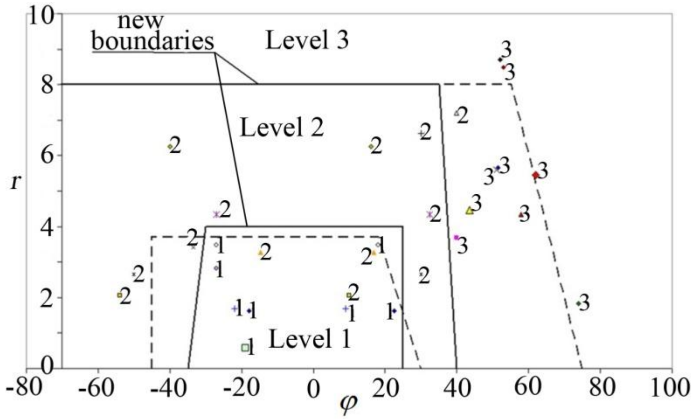

Fig. 8 Modified MAI criterion with r and $\Delta\varphi$ determined from the pilot composite model.

2) The "new MAI criterion"

The Hess structural model [16] has been subjected to a number of modifications [9, 15, 17]. The parameters for the modified pilot structural model are selected using a parameter optimization procedure via error variance minimization. The latest modification [17] extends the potential of the model to evaluate various inceptor parameters and their types, such as the active central/side stick and force/displacement sensing control of the pilot behavior. However, an attempt to use this model when calculating the resonant peak of a closed loop system (a key parameter of the MAI criterion) yielded a poor correlation between the results and the boundaries of the initial criteria. Only 52.1% of the configurations were predicted correctly with none of the first level configurations and only 31.23% of the third level configurations being correct (see Table 5).

Table 5 New MAI criterion for FQ and PIO predictions

New MAI criterion				
Boundaries	Total	Level 1	Level 2	Level 3
Initial version	25 out of 48 52.1%	0 out of 11 0%	20 out of 21 95.2%	5 out of 16 31.3%
Modified criterion	44 out of 48 91.6%	11 out of 11 100%	17 out of 21 81%	15 out of 16 93.8%

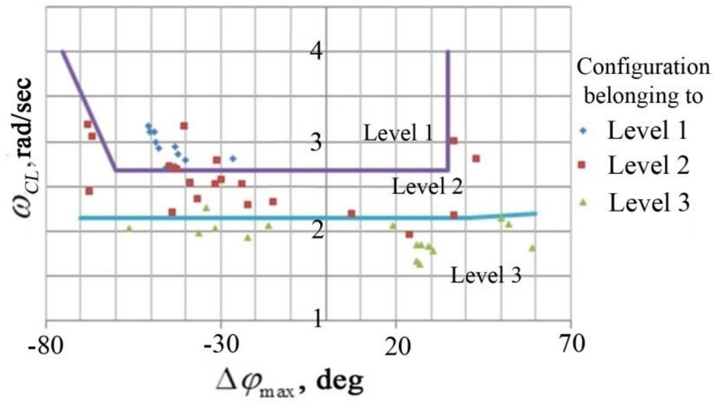

Fig. 9 New MAI criterion.

An attempt was made to find another parameter for the pilot-aircraft closed loop system featuring an improved correlation with the pilot's rating. The parameter in question was found to be the bandwidth ω_{CL} of the pilot-aircraft closed loop system. It was accepted as the frequency corresponding to the phase of the pilot-aircraft closed loop system equal to -90 deg. The calculations of this parameter and the pilot compensation parameter $\Delta\varphi$ allowed a new criterion to be obtained (see Fig. 9) with a high probability of making a correct prediction (see Table 5).

3) The criterion to predict the FQ in the probe-and-drogue refueling

A criterion was developed following the experiments performed in [18, 19], with 21 configurations investigated in a probe-and-drogue refueling task [20]. In addition to aircraft dynamics with conventional types of response, the configurations also implemented new response types (attitude command attitude hold (ACAH), rate command attitude hold (RCAH), and Extended RCAH). At the preliminary stage of each experiment, the final mission stage (that is, as soon as the distance between the pilot and the drogue reached $L \leq 5-8$ m) was when the pilot should close the single-loop system with the output coordinate $\varepsilon L = H + \theta L$ (where H is a change of the altitude at the pilot's location, and θ is the path angle) and utilize the additional information about the aircraft position relative to the tanker. The experiments were conducted under both non-stationary and stationary conditions (i.e., when $\dot{L} \neq 0$ and $\dot{L} = 0$, respectively). The principal part of the FQ estimation experiments was conducted under stationary conditions at a distance of $L = 7$ m, which best describes the difficulty of the considered task. These conditions are nearly the same as the recommendations proposed in Ref. [21] to estimate the handing qualities in the probe-and-drogue refueling. Other experimental conditions were also specified, including the ratio $\frac{d_{des}}{d_i} = 0.5$, where $d_i = 4\sigma_i$, σ_i is the root mean square of the input signal with $d_{des} = 0.4$ m and $\sigma_i = 0.2$ m, and $d_{ad} = 0.58$ m.

The experiments were conducted on a workstation by two pilots with the 12 so-called Have GAS PIO configurations investigated in Ref. [20], as well 9 configurations with conventional types of responses. The general form of the pitch angle transfer function for the Have GAS configurations is given by the following:

$$W_C^{\theta} = \frac{\theta(s)}{\delta_e(s)} = W_{pr} \frac{k_C(s + 1/T_q)}{s(s^2 + 2\xi\omega s + \omega^2)} W^*$$

where W^* is the high frequency approximation of the aircraft dynamics ($W^* \cong e^{-0.025s} W_a$), W_a is the actuator dynamics characterized by the second order system ($W_a = \frac{0.125}{(\frac{s^2}{26^2} + 2\frac{0.7}{26} + 1)}$), and the filter W_{pr} realizes the different types of aircraft responses. The aircraft response when W_{pr} =1 is of the RCAH type, and the $W_{pr} = \frac{s+0.5}{s + 1/T_q}$ and $W_{pr} = \frac{s}{s + 1/T_q}$ are considered the Extended RCAH and ACAH aircraft response types. The values for the parameters $1/T_q$, ξ, and ω are given in Table 6. The symbols for configurations in the left column of the table correspond to the different types of FCSs as defined in Table 7.

Table 6 Parameters for the different configurations

Configuration	$1/T_q$, (1/sec)	[ξ, ω], (1/sec)
R1, RX1, A1	2.0	[0.7, 2.6]
R2, RX2, A2	2.5	[0.7, 3.65]
R3, RX3, A3	3.0	[0.7, 4.82]
R4, RX4, A4	3.5	[0.7, 6.21]

$$n(\alpha) = 18\, g / rad, V_T = 456\, ft / sec$$

Table 7 Table of symbols

Type of FCS				
RCAH	R1	R2	R3	R4
Extended RCAH	RX1	RX2	RX3	RX4

ACAH	A1	A2	A3	A4

The dynamics of the configurations for the conventional types of responses were close to the Neal-Smith configurations with slight differences in the short period frequency, ω_{sp}. The values for the 2D, 4A, 5A, 2A, and 5D configurations were less than 9-10% relative to the ω_{sp} of the Neal-Smith configuration. The measurement results of the normalized resonance peak $\bar{r} = \frac{r}{r|_{W_{C_{opt}}}}$ for the closed loop system, the pilot compensation parameter $\Delta\varphi$, and the averaged pilot rating for all configurations are given in Table 8 and Fig. 10. Modifications to the FQ levels shown in Fig. 10 increased the accuracy of the FQ prediction to 95%. The calculations of these parameters are from the mathematical modeling of a pilot-aircraft system using the optimal pilot model. The relevant modeling algorithms can be found in Ref. [18].

Table 8 Results of the experimental investigations

Neal-Smith									
Configuration	1D	2D	4A	5A	1B	2A	1E	4D	5D
$\bar{r}$	7.46	2.8	4.2	2.8	6.1	3	6.47	5.8	3.02
$\Delta\varphi$, deg	102	96	80.9	87.3	95.1	90.1	112	93.2	94.4
PR	5.5	3	2.5	2.5	4	2.5	7	4.5	4.5

Have GAS												
Configuration	R1	R2	R3	R4	RX1	RX2	RX3	RX4	A1	A2	A3	A4
$\bar{r}$	6.96	7.02	6.35	4.87	8.6	5.35	4.65	3.44	2.61	0.26	-1.6	-1.8
$\Delta\varphi$, deg	102	91.7	93.4	90.4	83.7	85	79.1	80.6	89	75.5	75.8	72.4
PR	7	7	6	5	7	6	5	3.5	4.5	3.5	2.5	2.5

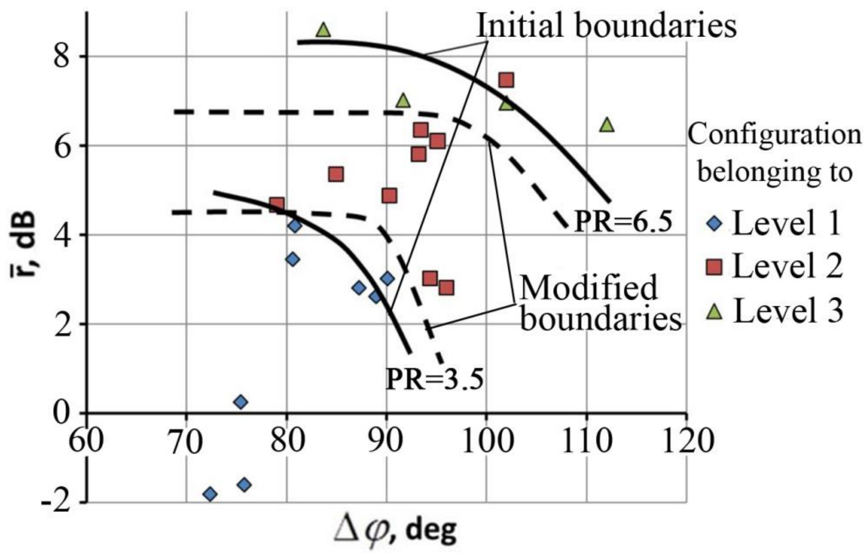

Fig. 10 Criteria for FQ prediction in refueling tasks.

B. Calculated pilot ratings of FQ as the criteria

The concept of calculating the pilot's ratings as a function of performances that characterize the accuracy (the mean square error) and the pilot compensation was first proposed by Anderson [22] and Dillow [23]. A number of the same types of criteria were developed at the PVL. It was asserted that the pilot's rating PR was determined by the elements of the ratings PR_i, where PR_j depends on the specific features ("*i*" and "*j*") as shown by [24]

$$PR = \max(PR_i, PR_j \ldots) \qquad (2)$$

1) The criterion to predict the pilot's rating in a single-loop tracking task

This criterion was developed as a result of ground-based simulations for a single-loop pilot-aircraft system in pitch tracking tasks with the same input signal that was used in the development of the MAI criterion to predict the FQs. The tests were performed for 23 configurations from the Neal-Smith database and 16 configurations from the Have PIO database.

The analysis of the pilot-aircraft system parameters as measured from the experiments (including the accuracy, the open loop, the closed-loop, and a pilot describing the function's parameters) demonstrated that all the configurations could be divided into two groups. The pilot's ratings of group one were correlated with the root mean square error σ_e, as shown in Fig. 11. The accomplishment of tracking tasks with these configurations was accompanied by a considerable lead compensation. The pilot compensation parameter $\Delta\varphi$ was positive for all the configurations. The pilot's ratings for group two were correlated with the parameter $\Delta\varphi$, which was negative for all the configurations, as shown in Fig. 12. Therefore, the following individual ratings were obtained:

$$PR_{\sigma} = 11(1 + \ln \sigma_e)$$

$$PR_{\Delta\varphi} = -0.11\Delta\varphi$$

Here, σ_e and $\Delta\varphi$ are the performances as measured through experiments. Figure 13 shows the correlation between the predicted pilot's ratings found from Eq. (2) and the in-flight ratings for the Neal-Smith configurations. The results for the Have PIO are the same.

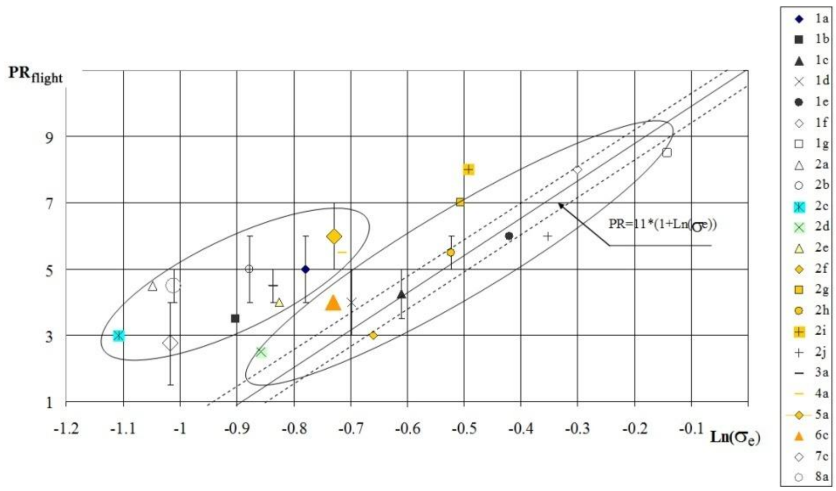

Fig. 11 Dependence of PR on σ_e.

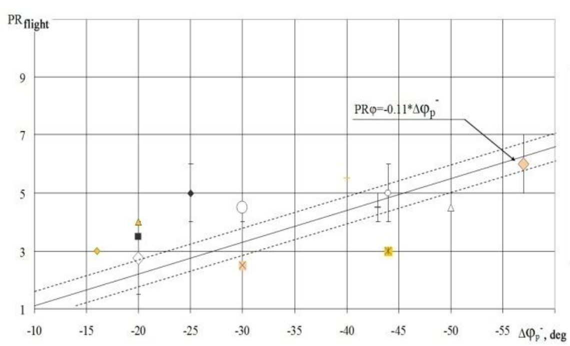

Fig. 12 Correlation between the PR and the parameter $\Delta\varphi$.

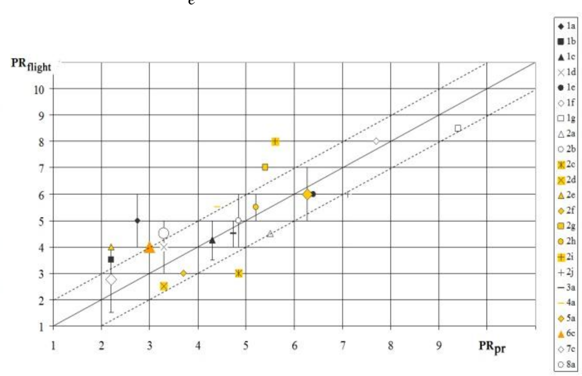

Fig. 13 Correlation of the in-flight ratings and the calculated pilot's ratings.

These correlations can be improved by excluding "unreliable" configurations. To this end, two types of pilot models were used to determine the parameters σ_e and $\Delta\varphi$ to mathematically find the pilot's rating: the modified structural model and the optimal pilot model. The analysis of the results demonstrates the necessity of modifying the equations that define the correlations between the individual ratings and the performances of σ_e and $\Delta\varphi$ when mathematical modeling is used for the predictions. Expressions for the structural and optimal pilot models are respectively given as [25]

$$PR_\sigma = 11(1+\ln(-0.4+1.68\sigma_e) \qquad PR_\varphi = -0.11(14+\Delta\varphi)$$

and

$$PR_\sigma = 11(1+\ln(-0.052+1.126\sigma_e) \qquad PR_\varphi = -0.11(0.952\cdot\Delta\varphi_p)$$

The in-flight pilot's rating and the calculated value $PR = max(PR_\sigma, PR_\varphi)$ were compared for a limited number of configurations with PR values from 2-5. The results demonstrate that differences between the calculated and the in-flight ratings did not exceed a single PR unit.

0) Predictions of the pilot's ratings in multichannel tracking tasks

The same approach for the pilot's rating assessment was also used for the FQ estimation in multichannel and multimodal pilot-aircraft systems. An analysis of the experimental results from various dynamics demonstrated that whenever a pilot performed roll-and-pitch tracking tasks simultaneously, the PR were given by $PR = max(PR_\gamma, PR_\varphi)$ [24], as shown in Fig. 14.

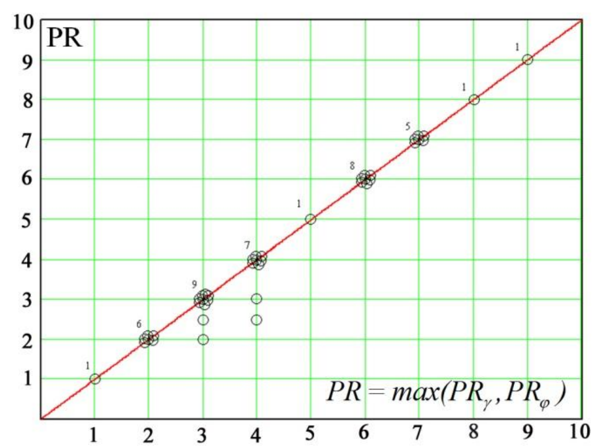

Fig. 14. Pilot's ratings vs individual ratings.

Here, the PR_θ, PR_φ, and PR are, respectively, the partial ratings for the FQ in the longitudinal and lateral channels, and the total pilot's rating given by the pilot following the experiments. It is obvious that each of the partial ratings of PR_θ and PR_φ are higher than the ratings PR_θ^1 and PR_φ^1 obtained for single-loop tracking tasks. Therefore, the individual ratings were found from the following equation

$$PR_{\theta,\varphi} = 1 + 5.36 \ln \frac{\sigma_{\theta,\varphi}}{\sigma_{\theta,\varphi}\big|_{W_{C_{opt}}}} \qquad (3)$$

which is in accord with the Weber-Fechner law.

The mean square errors $\sigma_{\theta,\varphi}$ in pitch-and-roll tracking tasks were determined from the pilot optimal model for the investigated controlled element dynamics. The $\sigma_{\theta,\varphi}\big|_{W_{C_{opt}}}$ are the mean square errors calculated for the case of the optimal control dynamics W_{Copt}. Table 9 gives the pilot limitation parameter values required to find $\sigma_{\theta,\varphi}$.

Table 9 Pilot model limitation parameters

	Time delay τ , sec	Time constant of neuromuscular system T_N , sec
Longitudinal channel	0.25	0.1
Lateral channel	0.3	0.25

The distribution of a pilot's attention was considered using the parameter f $(0 < f < 1)$ in the model for the power density of the perception noise

$$V_{\theta,\varphi} = \frac{K_{n_e}}{f_{1,2}} \sigma^2_{e_{\theta,\varphi}} \quad (4)$$

where $f_2 = 1 - f_1$. These parameters and Eq. (4) were used to optimize the pilot modeling. The variances σ_θ^2 and σ_φ^2 were calculated for each f_i and used to find the partial and total ratings from the equation

$$PR = \min_{f_1}[\max[PR_\theta,\ PR_\varphi]]$$

Only eight configurations from the first and second FQ levels were verified, and the modeling results agreed well with the experimental results with differences not exceeding 0.5-1 unit. It was demonstrated in [24] that the total pilot's ratings *PR* in a multichannel task could be determined from the partial ratings obtained under single-loop task conditions. The equation for the PR in this case is shown as

$$PR = PR_m + \sqrt{PR_m^2 - PR_\theta^* \cdot PR_\varphi^* + PR_m} \qquad (5)$$

where $PR_m = \frac{PR_\theta^* + PR_\varphi^*}{2}$, and PR_θ^*, and PR_φ^* are the pilot's ratings for the FQ assigned by a pilot following individually performed pitch-and-roll single-loop tracking tasks. Equation (5) was obtained with the requirement of

$$PR > \{PR_i^*\} \quad (6)$$

The analysis carried out in Ref. [10] demonstrates that Eq. (6) satisfies all the possible combinations of individual ratings obtained for the configurations considered in Ref. [26], and the total pilot's rating exceeded the in-flight ratings by only one unit. The total pilot rating PR is found by calculating the partial ratings $PR_{\theta,\varphi}$ using Eq. (3), where σ_θ and σ_φ are the mean square errors calculated from the simulations for the individual pitch-and-roll tracking tasks. It was shown in Ref. [10] that $\sigma_\theta |_{W_{Copt}} = 0.25 sm$ and $\sigma_\varphi |_{W_{Copt}} = 3.55 \deg$ if the variances of the input signal i(t) ($S_{ii} = \frac{k^2}{(\omega^2 + (0.5)^2)^2}$) is 4 sm^2 in the pitch channel and 452 deg^2 in the roll channel.

3) PR predictions considering motion cues

A number of studies on the influence of motion cues were performed at the PVL. The goal of one study was to develop a criterion to predict the lateral FQ due to considerable differences between the results obtained in the fixed-base and in-flight [27] tests. This was linked with the influence of the lateral acceleration n_y on the pilot's perception, and, consequently, on the pilot's ratings. In particular, the acceleration is dependent on the time constant of the aperiodic motion characterizing the aircraft roll dynamics and the pilot's head location relative to the X-axis l_p ($n_y = \frac{l_p}{g} \dot{p}$). Any decrease in the constant reduces the tracking error because the aircraft dynamics were near the integral, which also increases the acceleration. A detailed study of the various parameters for the transfer function $W_c = \frac{\varphi}{\delta_a} = \frac{K_c}{s(T_\varphi s + 1)}$ and the pilot's head position l_p was performed with a PVL moving-base simulator. The following equations for the partial ratings of the visual (PR^{vis}) and motion cues (PR^{vest}) as obtained from the pilot following the experiments [15]

$$PR^{vis} = -5.906 + 5.67 \ln \sigma_e$$

$$PR^{vest} = 34.43 + 11.66 \ln \sigma_{n_y}, \quad (7)$$

where σ_e and σ_{n_y} are the root mean square error of the roll angle and the lateral acceleration. The substitution of the measured σ_e and σ_{n_y} into Eq. (7) provides the total pilot's rating PR to give the FQ levels shown in Fig. 15. The figure shows that the first level is achieved at the time constant T_φ belonging to the interval from 0.26-0.95 sec, which is similar to the in-flight simulation results.

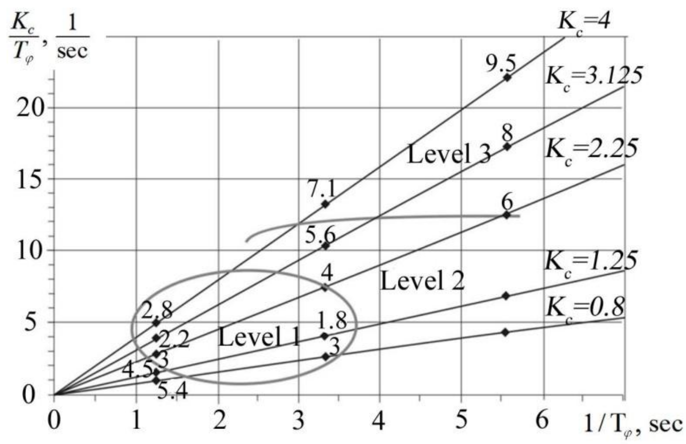

Fig. 15 FQ requirements for roll control tasks.

A separate series of experiments was carried out where a pilot gave individual ratings to the vestibular and visual factors (PR^{vest*} and PR^{vis*}respectively). An analysis of the results demonstrated that the ratings could be combined with the total ratings PR from the equation

$$PR = \max\{\mathrm{PR}^{vest*}, \mathrm{PR}^{vis*}\} - 3$$

The results of the experiments were applied to different parameters (K_C and T_φ) of the aircraft dynamics as characterized by the pilot's ratings $PR \le 4 - 4.5$, which provided the respective individual ratings PR^{vest*} and PR^{vis*} to determine the total ratings PR and to establish the first FQ level. It was demonstrated in Ref. [15] that the range of the parameter T from 0.26-1 sec was close to the previously mentioned interval.

The use of the pilot structural model implies using more accurate equations for the individual ratings, which are given as [15]

$$PR^{vis*} = -1.75 + 5.25 \ln(-4 + 2.5\sigma_e)$$

$$PR^{vest*} = 2.34 - 14 \ln(-4 + 2.5\sigma_e).$$

Using the above equations with Eq. (7) provided results that are close to the pilot's ratings as found in the experiments, as shown in Fig. 16.

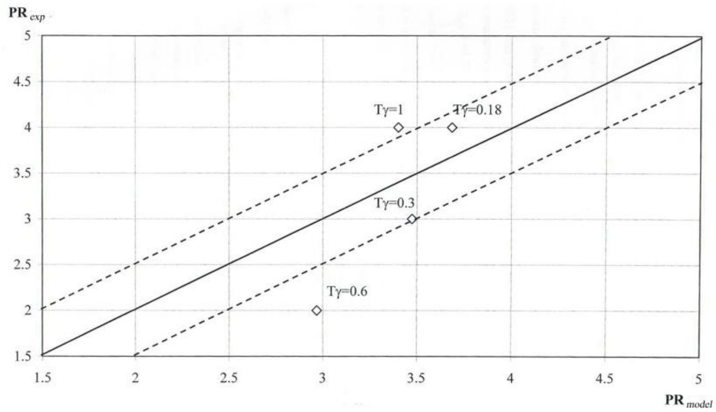

Fig. 16 Comparison between the pilot's ratings obtained from experiments and the mathematical modeling.

V. Relationship between requirements to the FQ and flight safety

The existing requirements for the FQ levels are defined in terms of the pilot's ratings [9]: $PR_{\max}$ of 3.5 for level one and 6.5 for level two. The MIL-F-9490 standard [9] recommends the following unreliability allowances for an entire flight control system, regardless of being manual or automatic

flight safety $< 5 \cdot 10^{-7}$ per flight class III airplanes;

$< 10^{-5}$ per flight class I, II, and IV airplanes.

The 14 CFR part 25 [28] stipulates a stricter requirement for the probability of an extremely improbable failure $< 10^{-9}$ per hour. Reference [10] attempted to find the relationship between the pilot's ratings and the probability of an accident. The author asserted that a pilot's rating was a random number with a Gaussian distribution and estimated the probability for whether a PR rating of 10 could be achieved, which would correspond to an accident, through a sudden change in the pilot's behavior, causing a sharp deterioration of the FQ. A dedicated study in this area was performed using an MAI simulator (Fig. 17) equipped with a computer generated visual system with a switched-off-moving-base system. The visual scene corresponded to a landing task on a concrete runway with images of several buildings and other details.

Fig. 17 Image of the MAI simulator.

Table 10 Task performances

Task performance	**[29]**	**[30]**	**MAI [24]**
		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 desired and adequate performances selected in Ref. [24] were practically the same as those in Refs. [29, 30], which are given in Table 10. According to Refs. [24, 29], the experiments were conducted in conditions of vertical wind gusts of $w(t) = A_w(1-\cos\frac{2\pi}{t^*}t)$, where $A_w = 2\,m/sec$ and $t^* = 10\sec$. The time duration corresponded to the entire number of gusts, which were stopped when the distance between the aircraft and touchdown point was 200-300 m. Two test pilots with over 1,200 flight hours on different types of aircraft and good experience in using the Cooper-Harper scale for FQ evaluations participated in the experiments. The experiments were conducted for several dynamic configurations from the Have PIO database (HP 2.1, HP 4.1, HP 3D, HP 3.8, and HP 3.12). More than 200 experiments were conducted with 18 to 24 experiments per configuration. The pilot's ratings for the Have PIO HP 4.1 configurations and their respective probabilities are given in Figs. 18 and 19 as illustrations.

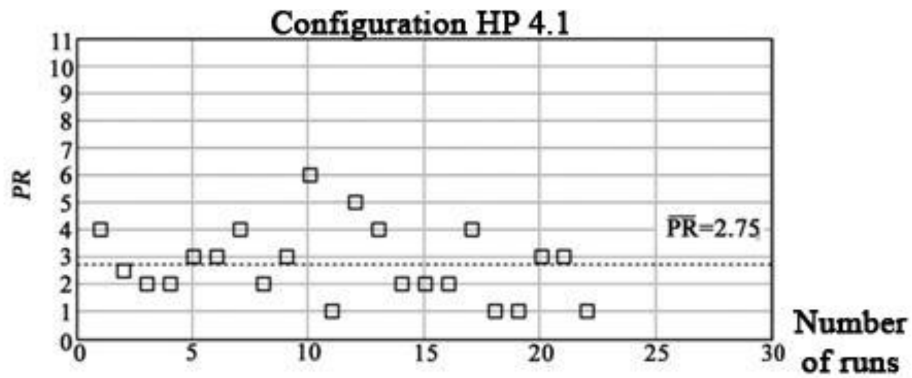

Fig. 18 The entire set of the pilot's ratings for configuration HP 4.1.

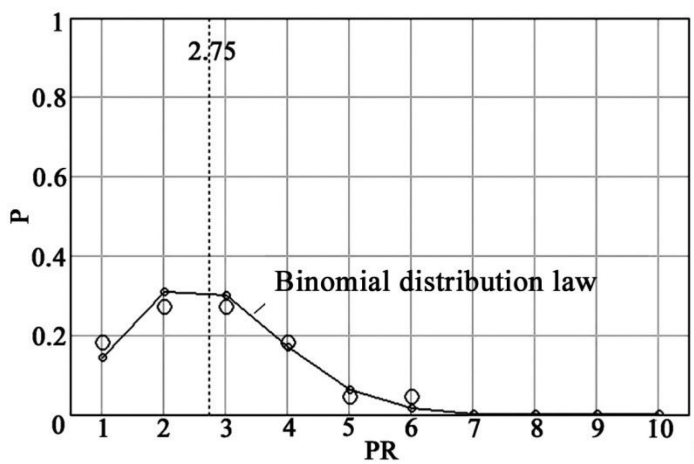

Fig. 19 Correlation between the probability of PR and the binomial distribution law.

The probabilities shown in Fig. 19 were calculated as the ratio of the number of specific ratings to the total number of ratings assigned by the pilots in the experiments with the associated configuration. Figure 19 also illustrates the binomial distribution law as expressed by the equation

$$p(PR) = C_9^{PR-1} p_*^{PR-1} (1-p)^{10-PR} \qquad (8)$$

where $p_* = \dfrac{\overline{PR}-1}{9}$, $C_9^{PR-1} = \dfrac{9!}{(PR-1)!(10-PR)!}$, and $\overline{PR}$ is the mean of the pilot's rating. It is seen that the results of the experiments are well aligned with the results of Eq. (8). This is expected, as rating corresponds to the key features of the random value distributed according to the binomial law.

The PR is a non-zero integer that cannot exceed a maximum value of 10. The function shown in Fig. 20 using Eq. (8) provides estimations for the probability that a PR value of 10 would be achieved if the mean pilot rating is equal to the PR^*. It is seen that the probability $p(\overline{PR}) = 10^{-5}$ for a $\overline{PR} = 3.5$.

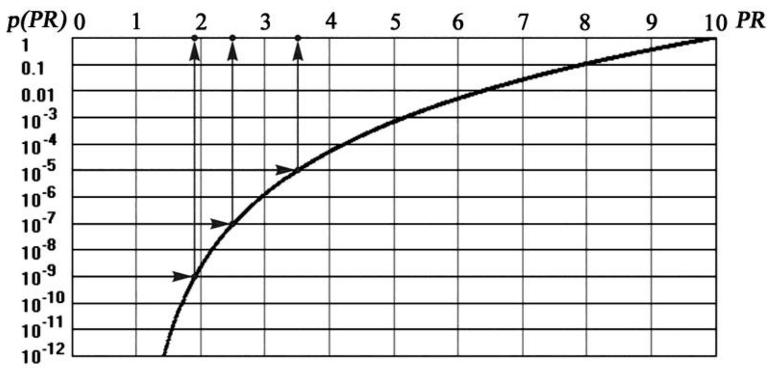

Fig. 20 Estimation for the probability of an accident.

The above results indicate that the requirement for the first level of the FQ formulated for class I, II, and IV airplanes is in accordance with flight safety requirements. For flight class III airplanes, the proposed flight safety requirement of $p(PR) < 5 \cdot 10^{-7}$ is true if PR<3 (e.g., PR=2.5). In the latter case, a sudden deterioration of the pilot-aircraft FQs due to a pilot's incorrect actions will not cause instabilities in the piloting process when PR=10. Whenever this technique is applied to passenger aircraft, which have a flight safety level of $< 10^{-9}$, the mean pilot's rating has to be less than 2. The above findings necessitate revising the current requirements to FQ levels.

VI. Conclusions

The proposed principle for the preliminary selection of configurations from well-known databases allowed modifications to the FQ and the PIO criteria, which are formulated as requirements to generalize the parameters for controlled element dynamics. The percentage of correct FQ and PIO-prone configuration predictions increased by 12.5-20% when the modified versions of the criteria were used. The percentage of correct predictions of the FQ levels and PIO prone configurations for the MAI criteria based on the requirements for the pilot-aircraft system parameters increased by 13-14% and 22-33%, respectively, for the modified boundaries of the FQ levels. It was demonstrated that the boundaries of the aircraft or pilot-aircraft system parameters were between the second and third levels of the FQ and divided the configurations into prone and non-prone PIO configurations. The proposed MAI criterion based on the requirements for the resonant peak and the bandwidth of the closed loop system was calculated using the pilot structural model. This criterion was characterized by improvements in the predictions of the FQ and PIO tendencies. The proposed set of criteria formulated as the calculated pilot's rating, which was the maximum of the individual ratings, allowed predicting the pilot's ratings in single-loop, multiloop, and multimodal tasks with a PR difference not exceeding 0.5-1.0 unit as compared with the ratings obtained under in-flight conditions.

The discovered relationship between the pilot's ratings and the probability of an accident necessitates modifications to the FQ level requirements for – class III airplanes. The maximum PR for the first level of the FQ must be less than 2.5 for this type of aircraft.

Acknowledgments

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