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Influence of Inceptors on Pilot-Aircraft System Characteristics and Flying Qualities

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Abstract. There are analyzed the results of experimental investigations of the feel system characteristics (inceptor's stiffness, side and central sticks, force and displacement sensing control type of inceptor) on pilot-aircraft system. The modification of the pilot structural model is considered. The mathematical modeling of pilot-aircraft system allowed to get close results to the experiments and to develop the criterion for flying qualities providing the potentiality to predict the influence of the feel system characteristics.

1. Introduction

One of the major problem in flight control system design is the determination of criteria for the flying qualities and pilot-induced oscillation prediction. The main part of them are the criteria defined in the terms of requirements to parameters of controlled element dynamics transfer function or its frequency response characteristics. Unfortunately they can not be used for selection of so-called feel system characteristics. The criteria for evaluation of these characteristics is practically absent mainly because of the limited number of researches carried out in this area. Only several of them including [1–8] were published during the last 20 – 25 years.

The results of the recent researches carried out at Moscow aviation institute and considered in this paper are the influence of some inceptor's characteristics including their type and type of signal transmitted from an inceptor to flight control system; technique and the criterion for prediction of their influence on pilot-aircraft system.

2. The experimental investigations on influence of feel system

The investigations of the stiffness was carried out for the central stick and side stick for a number of longitudinal configurations belonging to the first and third levels of flying qualities. The interval of a stiffness was 1 – 30 N/sm in case of the central stick and 5 – 15 N/sm in case of the side stick. It was studies also the influence of the type of control signal transmitted to the flight control system from the inceptor. Two of them: force and displacement defining so-called force sensing control (FCS) and displacement sensing control (DCS) types of inceptors were considered below.

All parameters of feel system were simulated with help of MOOG feel system (figure 1). The experiments were carried out on MAI moving based simulator (figure 2), equipped with computer generated visual system and MOOG feel system in all control channels.



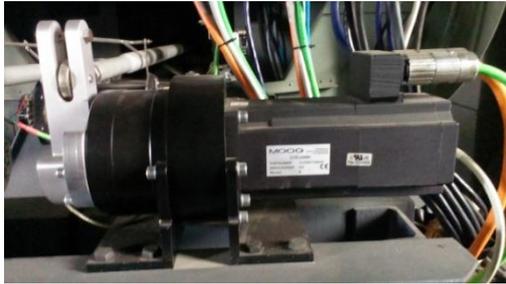


Figure 1. MOOG system for simulation of feel system parameters



Figure 2. MAI ground based simulator

The piloting task was the single-loop tracking task. The input signal was the sum of harmonics which frequencies and amplitudes were selected to provide the power spectral density equivalent to

$$\text{the following equation } S_{ii} = \frac{K^2}{(\omega^2 + 0.5^2)^2}, \sigma_i^2 = 4 \text{ cm}^2$$

The experiments carried out with the side stick for configurations HP 2.1 (I level of flying qualities) and HP 5.10 (III level of flying qualities) from Have PIO data base [9] demonstrated that in case of FSC side stick the pilot phase delay was considerably smaller. The phase delay was characterized by parameter $\Delta\varphi|_{\omega=10 \text{ rad/sec}} = \varphi_{FSC} - \varphi_{DSC}$, where φ_{FSC} and φ_{DSC} are the pilot phase frequency response characteristics for the FSC and DSC inceptors correspondingly defined at the frequency $\omega = 10 \text{ rad/sec}$.

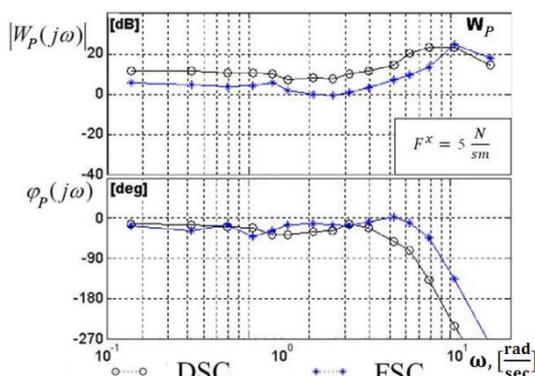


Figure 3. Pilot frequency response characteristics conf. HP 2.1

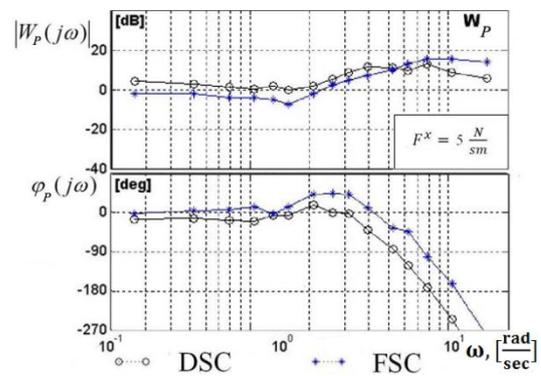


Figure 4. Pilot frequency response characteristics conf. HP 5.10

It was equal to 106 deg in the experiments with configuration HP 2.1 and the stiffness $F^x = 5 \frac{N}{sm}$ (figure 3). It means that the use of FSC type of inceptor decreases the time delay close to 0.18 sec. In experiments with higher stiffness, $\Delta\varphi|_{\omega=10 \text{ rad/sec}}$ decreases up to 40 deg at the same frequency.

Except it, the experiments with FSC inceptor were accompanied by the decrease of variance of error σ_e^2 in 1,5 times and the increase of crossover frequency ω_c up to 30 %.

As for configuration HP5.10 the influence of the type of inceptor (DSC or FSC) on the phase delay parameter $\Delta\varphi|_{\omega=10 \text{ rad/s}}$ is smaller and reaches 80 deg only (figure 4).

The similar effects were observed with the central stick too. They demonstrated more sufficient and specific influence of spring stiffness on the results. For example the function $\sigma_e^2 = f(F^x)$ has the minimum (see figure 5).

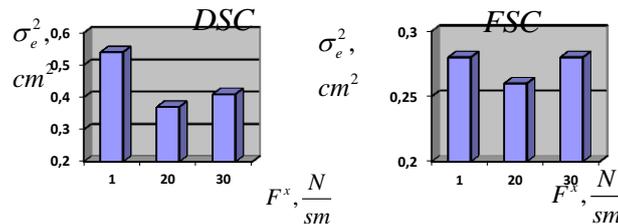


Figure 5. Influence of the stiffness on the variance of error

In case of the central stick, the difference between the pilot phase frequency characteristics in experiments with FSC and DSC type of inceptors was exposed too. The values of parameter $\Delta\varphi|_{\omega=10 \text{ rad/sec}}$ lie in the range 102 deg (conf. $\frac{K_C}{s(Ts+1)}) \div 74.4 \text{ deg}$ (conf. HP 5.10).

The influence of the central stick stiffness on pilot-aircraft system characteristics demonstrated also the decrease of the crossover frequency, resonant peak and bandwidth of closed-loop system in the case of an increase of stick stiffness.

The comparison of the accuracy achieved for the central and side sticks demonstrated higher crossover frequency and the smaller variance of error σ_e^2 in experiments with the side stick specially for the FSC type of inceptor (by 1.4 times for configuration HP-21). The same tendencies were exposed for the other dynamic configurations too.

3. Development of technique for prediction of flying qualities ensuring the selection the inceptor's characteristics

The development of criteria for FQ prediction requires the knowledge of data bases [9–11].

These data bases include 117 dynamic configurations. The experience in the use of criteria for FQ and PIO prediction demonstrates that the results of the prediction do not match often to the results of experimental investigations. One of the reasons of such disagreement is the imperfection of the data bases associated with:

- The limited number of flight tests executed for each configurations (in many cases only one test and one rating);
- Considerable variability of pilot ratings for some configurations. In some cases pilot ratings corresponded to the different FQ levels.

The averaging of such pilot ratings influences on the boundaries dividing the parameters on the ranges characterizing the specific FQ levels. It decreases the reliability of results and requires more accurate preliminary selection of the configurations for the following use of results of experiments.

Therefore it was offered to select the configurations from the data bases characterizing by more reliable in-flight results.

The “reliable” configurations were selected according to the following rules:

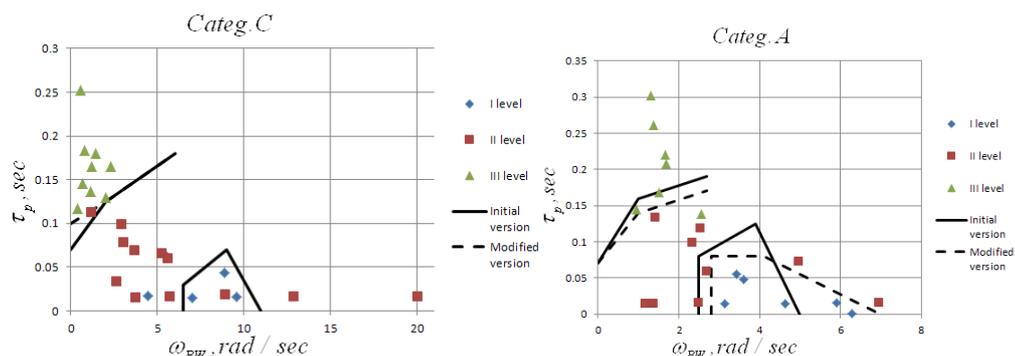
- A. The flying qualities of each configuration had to be evaluated at least two times;
- B. The configurations had to be evaluated by ratings belonging to the same FQ levels;
- C. The configurations related to the different levels with the difference of pilot ratings no more than one unit might be selected too.

Only 48 configurations (see table 1) from all data bases correspond to these rules. 11 configurations related to the first level of FQ, 21 configurations belong to the second level of FQ and 16 to the third level of FQ correspond to this rules.

Table 1. The configurations selected from the data bases

№	Conf.	PR	PIOR	Level	№	Conf.	PR	PIOR	Level
1	LH2.1	2; 2	1; 1	1	25	NS3E	4; 4	1.5; 1	2
2	LH4C	3; 3	1.5; 2	1	26	NS4A	5,5; 5	2.5; 2	2
3	NS1B	3,5; 3	1; 1.5	1	27	NS7G	5; 6	2; 2	2
4	NS2D	3; 2,5; 2,5	2; 1; 1	1	28	HP3.6	5; 4	2; 2	2
5	NS3C	4; 3	2; 1	1	29	NS6A	5; 6	2; 3	2
6	NS7C	3; 3; 4; 1.5	2; 2; 1; 1	1	30	NS8A	5; 4	2.5; 1	2
7	NS8C	3,5; 3	2; 1	1	31	NS6C	4; 5	2.5; 2	2
8	HP2.1	2; 2; 3	1; 1; 1	1	32	NS7E	6; 5	3; 2	2
9	HP3D	2; 2	1; 1	1	33	NS1F	8; 8	4; 4	3
10	HP4.1	3; 2; 3	1; 1; 1	1	34	NS1G	8,5; 8,5	4.5; 4	3
11	HP4.2	3; 3; 4	1; 1; 2	1	35	NS2I	8; 8	4.5; 4	3
12	LH 2A	4; 6	2; 2,5	2	36	NS4D	8; 9	3,5; 5	3
13	LH2.2	4; 4,5	2; 1	2	37	NS5D	8,5; 9; 9	4; 5; 4	3
14	LH3.0	4; 5	1; 2	2	38	NS5E	8; 8	4; 4	3
15	LH1C	4; 4	1; 1	2	39	HP2.5	10; 7; 10	4; 4; 5	3
16	LH1.1	4; 4	2; 1	2	40	HP2.8	8; 10; 8	4; 4; 4	3
17	LH2.7	7; 6	3; 3	2	41	HP3.12	7; 9	4; 5	3
18	LH3.6	7; 6	3; 3	2	42	HP3.13	10; 10	4; 5	3
19	LH4.4	7; 6	3; 3; 2	2	43	HP5.9	7; 8; 7	4; 4	3
20	NS2A	4,5; 4	2; 2	2	44	HP5.10	10; 10	5; 5	3
21	NS2H	5; 6; 5,5	2,5; 2,5; 2	2	45	LH1.3	9; 10	4; 4	3
22	NS2J	6; 6	2; 2	2	46	NS5C	9; 7	5; 5	3
23	NS3A	5; 4; 4; 4	3; 1,5; 1; 1,5	2	47	NS6E	8,5; 7	5; 4	3
24	NS3D	4; 4	2; 1	2	48	NS6F	8,5; 10; 8	4; 5; 4	3

The potentiality of the correct prediction with help of proposed rules is demonstrated below for two criteria. One of them is bandwidth-time delay criterion ($\omega_{BW} - \tau$) for prediction of flying qualities [12]. The initial and the final versions of this criterion are shown on figure 6

**Figure 6.** Criteria « $\omega_{BW} - \tau_p$ ».

The modified version allowed to increase the percentage of configurations predicted correctly from 81.3 % up to 93.8 %. Unfortunately this criterion is not sensitive to the evaluation of inceptor characteristics and it's type.

The other criterion is so-called MAI criterion [13] was defined in the terms of the resonant peak of closed-loop system r and pilot compensation parameter $\Delta\phi$. The last one was determined as the maximum difference between pilot phase response characteristics $\phi|_{W_c}$ and $\phi|_{W_{c_{opt}}}$ corresponding to

the considered configuration W_c and optimal controlled element dynamics $W_{c_{opt}}$ in all investigated frequency range $\Delta\omega$, $\Delta\varphi = \max_{\Delta\omega}(\varphi|_{W_c} - \varphi|_{W_{c_{opt}}})$.

The experiments carried out at one of MAI simulator with 66 Neal-Smith [9], Have PIO [10] and Lahos [11] configurations. The result of it is so-called MAI criterion [12] (initial version) shown on figure 7. The effectiveness of the proposed rules for selection of configurations and the following modification of criteria was investigated for the limited number of configurations (22 configurations) corresponding to this rules.

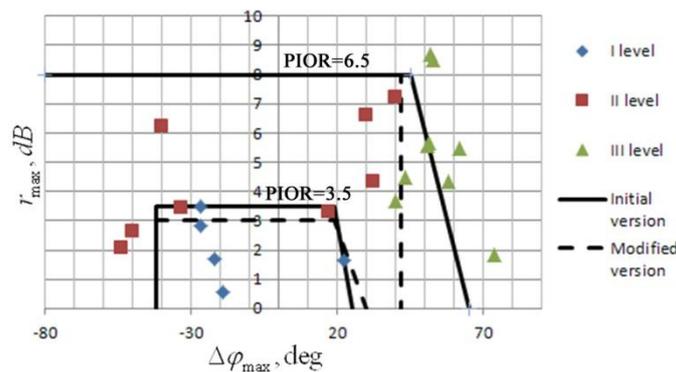


Figure 7. Modified MAI criterion with boundaries defined from experiment

The modification of the boundaries allowed to increase the number and percentage of configurations predicted correctly (up to 20 configurations and 90.9% instead of 77.2 % for the initial version of the boundaries).

Because the parameters of the criteria depend on the pilot and pilot-aircraft system parameters, which are sensitive to the different task variables, it was made the attempt to use the mathematical modeling of pilot-aircraft system with goal to calculate parameters r and $\Delta\varphi$. For that purpose the modified pilot structural model was used. The modification of this model was performed for evaluation the influence of feel system parameters on pilot-aircraft system characteristics and for selection of these parameters. The main modifications are the following:

- the separation of the limb-manipulator dynamics in two elements: dynamics of limb-muscle system and feel system dynamics;
- the introduction of additional motor noise n_c . The spectral density of this noise is $S_{n_c n_c} = 0.003\pi\sigma_c^2$;
- the extension of the cost function. The additional term $\beta\sigma_F^2$ was added to reflect the influence of the spring stiffness on pilot workload mentioned above and closed-loop system characteristics:

$$I = \sigma_e^2 + \alpha\sigma_c^2 + \beta\sigma_F^2.$$

The structural pilot model is shown on figure 8.

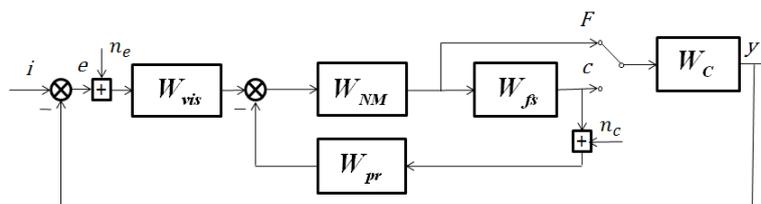


Figure 8. The structural pilot model

Here W_{fs} – the feel system dynamics;

W_{NM} – the limb muscle system dynamics $\left(W_{NM} = \frac{1}{T_{N^*}s + 1} \cdot \frac{e^{-\tau_N s}}{T_N^2 s^2 + 2T_N \xi_N s + 1} \right)$;

W_{vis} – pilot error compensation dynamic $\left(W_{vis} = \frac{K_L(T_L s + 1)}{T_I s + 1} e^{-\tau s} \right)$;

W_{pr} – proprioceptive feedback dynamic $\left(W_{pr} = \frac{K_n s^2}{T_n^2 s^2 + 2T_n s + 1} \right)$;

n_e – perception noise. Its power spectral density $S_{n_e n_e} = K_{n_e} \pi \frac{\sigma_e^2 + \sigma_{\dot{e}}^2 T_L^2}{1 + T_L^2 \omega^2}$, $K_{n_e} = 0.01$.

The minimization of the cost function allowed to define the parameters T_L, K_L, T_n, K_n (see the fig. 10). The other parameters of the model were constant and equal to $T_{N^*} = 0.02$ sec, $T_N = 0.1$ sec, $T_I = 0.01$ sec, $\xi_N^* = 1.2$, $\tau = 0.2$ sec, $\tau_N = 0.08$ sec. The weighting coefficient β was accepted 0.001.

The procedure for the minimization of the cost function assumes the calculation of variance $\sigma_e^2, \sigma_{\dot{e}}^2, \sigma_c^2$ from the following equations:

$$\begin{cases} A_1 \sigma_e^2 + B_1 \sigma_{\dot{e}}^2 + C_1 \sigma_c^2 = \sigma_{e_i}^2 \\ A_2 \sigma_e^2 + B_2 \sigma_{\dot{e}}^2 + C_2 \sigma_c^2 = \sigma_{\dot{e}_i}^2 \\ A_3 \sigma_e^2 + B_3 \sigma_{\dot{e}}^2 + C_3 \sigma_c^2 = \sigma_{c_i}^2 \end{cases}$$

Here the symbols \dot{e} and \dot{e}_i are the derivatives of error. The component \dot{e}_i is correlated with the input signal. The signal c is the displacement signal and c_i is its part which is correlated with the input signal.

The coefficients A_i, B_i and C_i are defined by the corresponding closed-loop transfer function, for example:

$$\begin{cases} A_1 = 1 - \frac{K_{n_e}}{\pi} \int_0^\infty \left| \frac{W_P W_C}{1 + W_P W_C} \right|^2 \frac{d\omega}{1 + T_L^2 \omega^2} \\ A_2 = - \frac{K_{n_e}}{\pi} \int_0^\infty \left| \frac{W_P W_C}{1 + W_P W_C} \right|^2 \frac{\omega^2}{1 + T_L^2 \omega^2} d\omega \\ A_3 = - \frac{K_{n_e}}{\pi} \int_0^\infty \left| \frac{W_P}{1 + W_P W_C} \right|^2 \frac{d\omega}{1 + T_L^2 \omega^2} \end{cases}$$

For FSC inceptor type $W_P = W_{vis} \frac{W_{NM}}{1 + W_{NM} W_{pr} W_{fs}}$

For DSC inceptor type $W_P = W_{vis} \frac{W_{NM} W_{fs}}{1 + W_{NM} W_{pr} W_{fs}}$

With help of the modified structural model the influence of stiffness and type of inceptors (FSC or DSC) was investigated. The results of the modeling demonstrated the same influence of the investigated parameters on pilot-vehicle system characteristics as in experimental investigations and a good agreement between the results of experimental and mathematical modeling (figures 9-11).

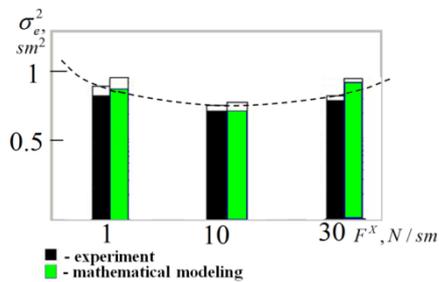


Figure 9. The influence of the stiffness

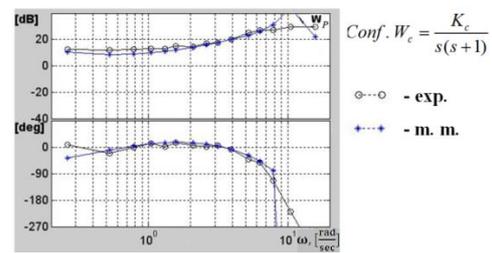


Figure 10. The agreement between the mathematical modeling and experimental results

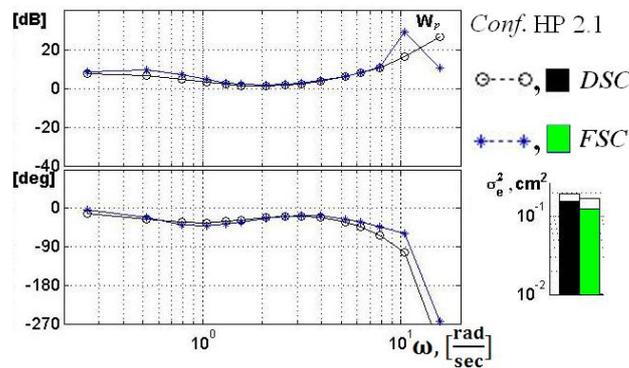


Figure 11. The influence of the type of inceptor (mathematical modeling)

The modified model allowed also to expose the difference between pilot frequency response characteristics for the different types of inceptor discussed above (figure 11).

However the attempt to use it for the calculation of resonant peak of the closed-loop system (the key parameter of MAI criterion) demonstrated bad correlation of the results with the boundaries of initial criteria. Only 52.1 % of configurations were predicted correctly (no one configuration from the first level and only 31.23% of configurations from the third level).

Because of it the attempt was undertaken to find the other parameter of closed-loop system characterizing by the better correlation with pilot rating. It was defined that such parameter is the bandwidth ω_{BW} of the close-loop system. It was accepted as the frequency corresponding to the phase of closed-loop system equal to -90 deg.

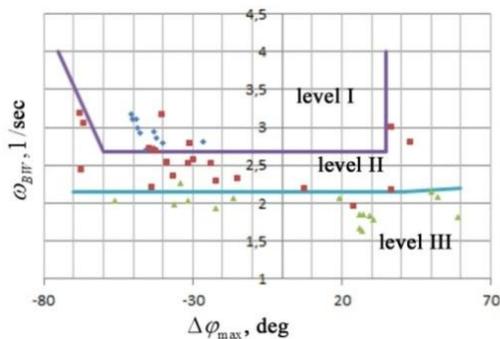


Figure 12. “New” MAI criterion

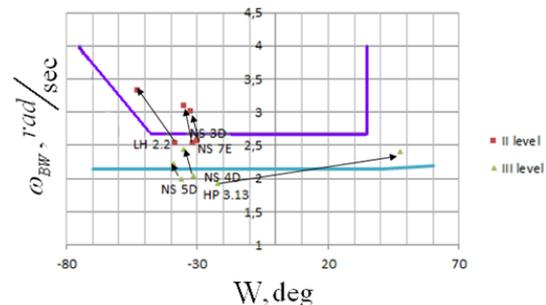


Figure 13. Evaluation of configurations with the different types of inceptor

The calculation of the parameters $\Delta\varphi$ and ω_{BW} with help of the pilot structural model allowed to get the new criterion (figure 12) characterized by high potentiality of the correct prediction.

This criterion provided 91.6 % of correct FQ prediction. It was used for the evaluation of flying qualities for two types of inceptor: DSC and FSC types.

It is seen (figure 13) that the flying qualities of configurations related to the third level (case of DSC) were improved in case when FCS type of inceptor and is used. In the last case flying qualities related to the second level of FQ. The same tendency takes place for flying qualities of the configurations related to the second level and equipped with the DCS type of inceptor. The same configurations are transformed to the first level flying qualities in case of use of FSC inceptor.

3. Conclusion

The investigation demonstrated that the use of FSC type of inceptor allows to achieve the considerable decrease of time delay in the pilot describing function (up to 0.18 sec), the improvement of the accuracy (in 1.5 times) and the increase of crossover frequency of pilot-aircraft open-loop describing function (30 % reduction). The inceptor's stiffness has a optimum value providing the minimum of error both for DSC and for FSC inceptor. Its increase causes the decrease of resonant peak of close-loop system and crossover frequency. The side stick provides higher accuracy and resonant peak in comparison with the central stick. The criteria for the prediction of flying qualities allowed to predict them with high probability and to evaluate the influence of feel system characteristics on flying qualities was developed too.

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