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EFFECT OF FEEL SYSTEM CHARACTERISTICS ON PILOT MODEL PARAMETERS

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Abstract

The paper presents recent experimental data on the effect of control manipulator feel system characteristics, such as force gradient and damping, on the pilot model. The analysis of the effect is conducted on the basis of describing functions identified in compensatory roll tracking task. Identification of the limb-manipulator frequency responses was possible by introducing an input signal to the manipulator loading system. The analysis shows that force gradient variation affects neuromuscular describing function, demonstrating adaptation of pilot to manipulator force variation. Due to the adaptation, the limb-manipulator cutoff frequency remains constant within the force gradients assessed by the pilots as optimum. The feel system damping does not demonstrate any noticeable effect on limb-manipulator describing function. Taking into account, the limb-manipulator operation changes the traditional presentation of pilot model transfer function at frequencies above 6-8 rad/s.

1 Introduction

The selection of manipulator feel system characteristics is usually made empirically on the basis of pilot comments and experience in using manipulators of the similar type. Recent theoretical approach [1] developed to select optimum feel system and control sensitivity characteristics is a comprehensive tool, though based on subjective pilot ratings. No objective data or criteria have been found so far to confirm the optimality of the selected manipulator feel system characteristics.

Piloting accuracy is often tried to be used as objective parameter to assess aircraft handling qualities. The data in Figure 1 shows that piloting accuracy does not change within the very wide range of force gradient and damping variation and, thus, it can not be used for objective criterion to assess feel system characteristics optimality.

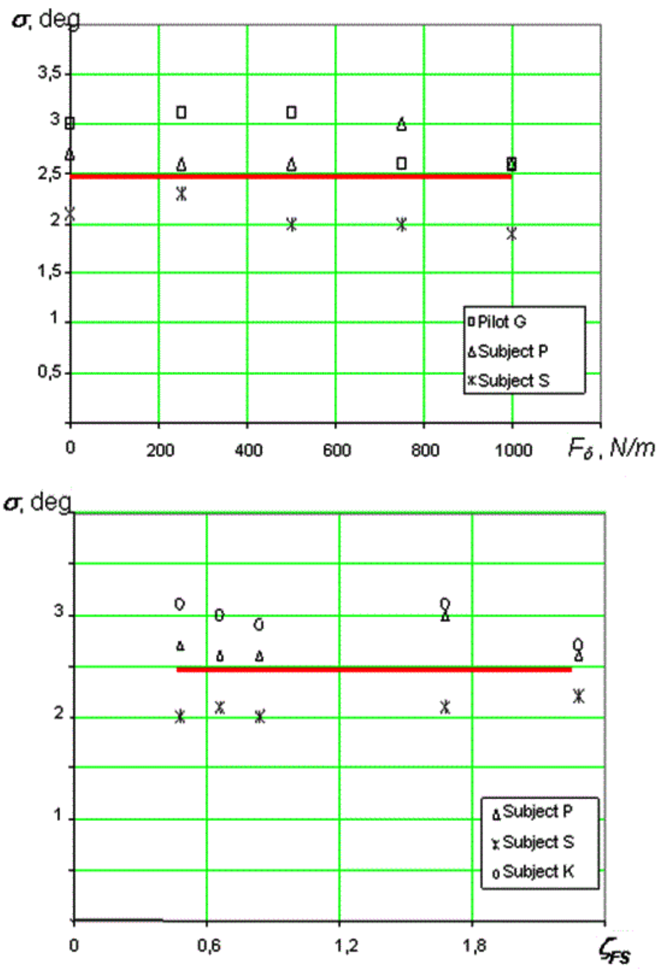

Fig. 1. Tracking accuracy as a function of manipulator force gradient (F_δ) and damping ratio (ζ_{FS}).

As compared to piloting accuracy, pilot models are more effectively used for objective assessment aircraft handling qualities, for example [2], [3]. Pilot models describe human pilot control activity, which is performed by means of the control manipulator. Thus, it is natural to suppose that manipulator feel system characteristics can affect pilot control activity, which can be traced by changing of pilot model parameters. This study has been done to determine the effect feel system characteristics on pilot model and its components, such as central nervous system, limb-manipulator system, neuromuscular system, and to find objective confirmation of manipulator feel system optimality.

Manipulator feel system characteristics are completely described by force gradient (F_{δ}), damping (dimensional $F_{\dot{\delta}}$ or damping ratio ζ_{FS}), breakout force (F_{br}) and friction (F_{fr}). The force gradient and damping present the greatest research interest. Friction and breakout force can be assumed given, since the friction is considered a negative aspect and minimized, and breakout force is selected to compensate for the friction (to provide manipulator returning to the neutral position when released) and to avoid unintended cross coupling of pitch-roll control activity.

2 Experimental Procedure

The goal of experiments was to determine the effect of force gradient and damping on pilot model parameters.

Experiments were conducted on TsAGI Flight Simulator FS-102. Two types of control manipulator were used: a traditional wheel and a sidestick. The manipulators were loaded with electrical loading system of MOOG. Manipulator forces were modelled according to the following equation:

$$m\ddot{\delta} + F_{\dot{\delta}}\dot{\delta} + F_{\delta}\delta + F_{br}sign(\delta) + F_{fr}sign(\dot{\delta}) = 0 \quad .$$

In experiments, force gradient F_{δ} and $F_{\dot{\delta}}$ damping were varied (see Tables 1 and 2); manipulator inertia, breakout and friction force remain unchanged and were equal: m=2.5 *kg* (5.5 *lb*) for the wheel, m=3.5 *kg* (7.7 *lb*) for the sidestick, F_{br} = F_{fr} =0.

Table 1. Varied parameters for the sidestick.

F_{δ} at $F_{\dot{\delta}}$ = 70 N/m/s (0.4 lb/in/s)	$F_{\dot{\delta}}$ at F_{δ}=500 N/m (2.83 lb/in)
0 N/m (0 lb/in)	40 N/m/s (0.23 lb/in/s)
250 (1.41)	55 (0.31)
500 (2.83)	70 (0.4)
750 (4.24)	110 (0.62)
1000 (5.66)	140 (0.8)
—	190 (1.07)

Table 2. Varied parameters for the wheel.

F_{δ} at $F_{\dot{\delta}}$ = 27 N/m/s (0.15 lb/in/s)	$F_{\dot{\delta}}$ at F_{δ}=203 N/m (1.15 lb/in)
0 N/m (0 lb/in)	0 N/m/s (0 lb/in/s)
203 (1.14)	27 (0.153)
400 (2.26)	45 (0.255)
800 (4.52)	—

Three human operators and two test pilots participated in experiments. Each configuration of feel system characteristics was flown at least 3 times. Pilot comments and tracking accuracy were recorded.

Pilot model identification was performed for compensatory roll tracking task. The control object dynamics was described by the single roll motion with roll mode time constant equal 0.7s, which correspond to a civil airplane.

The pilot model structure used for the model parameters identification is shown in Figure 2. To identify describing functions of the limb-manipulator system and components, an additional force input *f(t)* is introduced into manipulator loading system. Forcing functions *i(t)* and *f(t)* are sum of sines with different frequency spectra (Fig. 3).

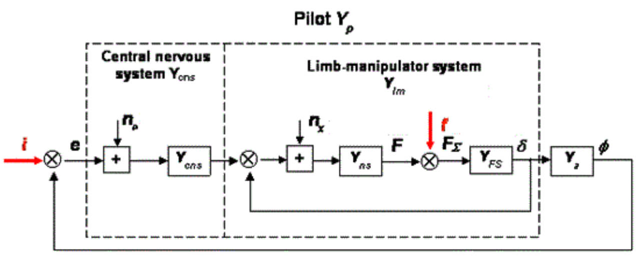

Fig. 2. Structure of pilot model in roll tracking task.

Nonparametric identification of pilot model describing functions is conducted with use of Fourier transform, and the describing functions are calculated by means of cross-spectral densities.

For example:

$Y_p(j\omega)=\dfrac{S_{\delta i}}{S_{ei}}$ for pilot model;

$Y_{lm}(j\omega)=\dfrac{S_{\delta i}S_{ei}S_{ff}-S_{\delta f}S_{ii}S_{F\Sigma i}}{S_{\delta i}S_{ei}S_{ff}}$ for limb-manipulator closed loop system.

The adequacy of calculation was checked by comparison of the feel system and control object describing functions with their identified characteristics.

An example of the identified pilot model describing functions are shown in Figure 4.

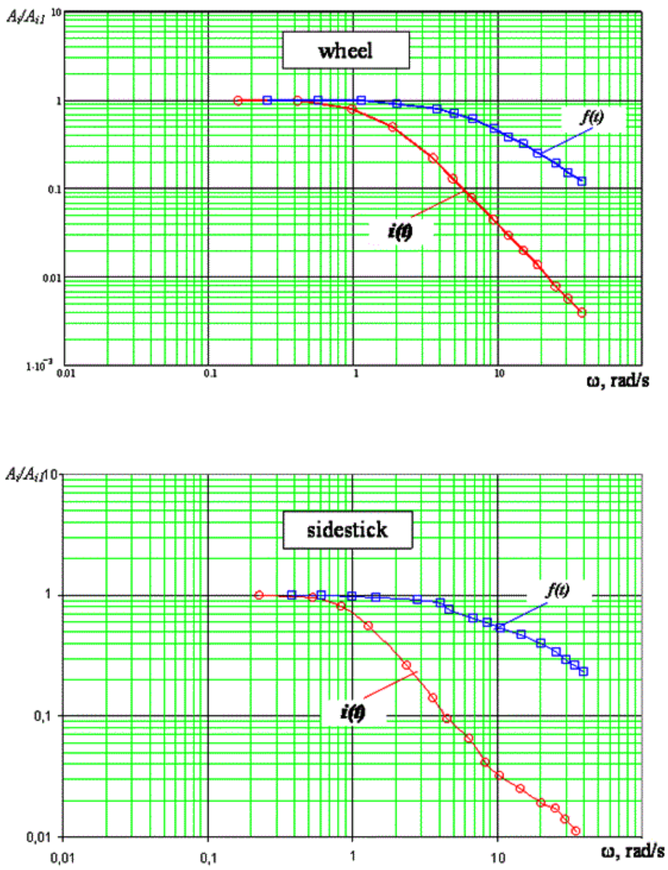

Fig. 3. Visual *i(t)* and force *f(t)* forcing functions used in roll tracking task with wheel (upper picture) and sidestick (lower picture).

3 Analysis of the Data Received

Analysis of the identified describing functions showed the following:

1. General observations. All regularities of the feel system characteristics effects are similar in kind for a traditional wheel and sidestick.

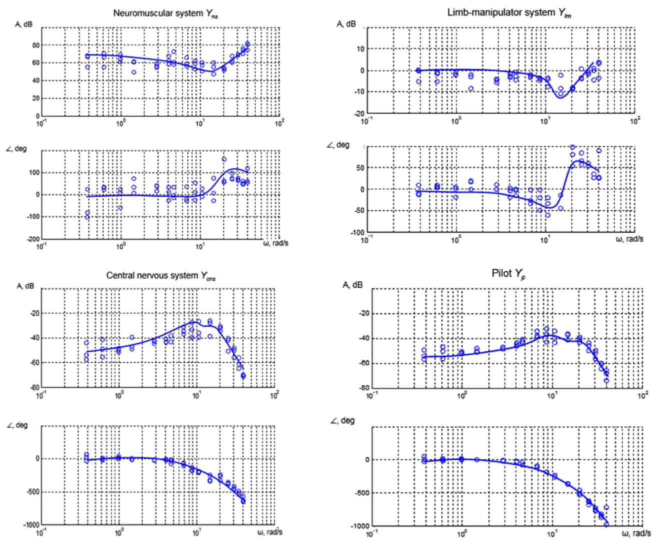

Fig. 4. An example of the identified describing functions of different components of pilot model (with the average line in blue).

2. *Central nervous system and pilot model as a whole.* As it is seen from describing functions, the pilot model is completely determined by its central nervous system, which is characterized by the two resonant peaks at frequencies 6-8 rad/s and 18-20 rad/s. The peaks are determined, obviously, by limb-manipulator system operation. Thus, the commonly used description of the central nervous system should be completed as follows:

$$Y_{cns}(s)=Ke^{-s\tau}\frac{T_1s+1}{T_2s+1}\cdot\frac{1}{T_3^2s^2+2\varsigma_3T_3s+1}\cdot\frac{1}{T_4^2s^2+2\varsigma_4T_4s+1}$$

where:

τ, T_1, T_2 are determined by visual input tracking and depend on control object dynamics: for roll model time constant 0.7 s the coefficients can be assumed equal τ=0.2*s*, T_1=1.0*s*, T_2=0.05*s*;

T_3, T_4, ζ_3, ζ_4 are determined by limb-manipulator system operation. Their changes caused by changes in force gradient and damping are not clearly seen, and, thus, for all values of feel system characteristics considered in the course of the work they can be assumed equal:

for wheel: T_3=0.143 s, T_4=0.055 s, ζ_3=0.5, ζ_4=0.3;

for sidestick: T_3=0.114 s, T_4=0.065 s, ζ_3=0.45, ζ_4=0.2.

3. *Neuromuscular system.* The describing function of the neuromuscular system is similar in kind for different values of force gradient and damping. It is similar as well to those identified by other authors (see [4], for example). The magnitude of the function has a noticeable droop in between 6 and 25 rad/s, i.e. at frequencies corresponding to the feel system resonant peak. As gradient F_δ increases, the droop size increases as well (Fig.5). It means that the neuromuscular system compensates for the feel system resonant peak increasing with force gradient. This fact indicates the neuromuscular capability to adapt to manipulator force increase.

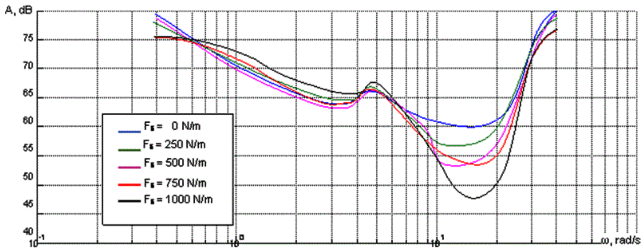

Fig. 5. Averaged frequency responses of neuromuscular system for different force gradients (sidestick).

Effect of force gradient on the neuromuscular magnitude at frequencies below 6 rad/s and above 25 rad/s is not clearly seen, yet there is some magnitude increasing at low frequencies as gradient increases from 500 to 1000 N/m.

It is seen from Figure 6 that damping variation does not cause any noticeable or regular effect on neuromuscular magnitude at any frequencies. It means that the neuromuscular system is not sensitive to the damping variation and does not demonstrate any adaptation. This is due to the fact that the damping increase does not change the total manipulator forces and handling qualities ratings (at least at the frequencies typical of piloting).

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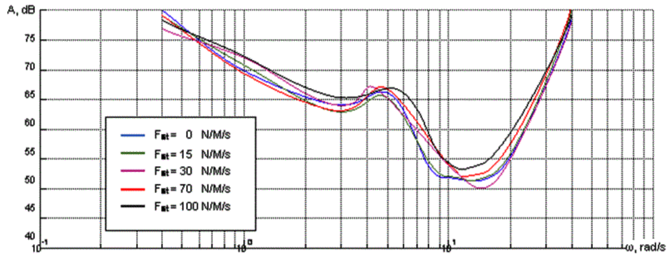

Fig. 6. Averaged frequency responses of neuromuscular system for different damping (sidestick).

To confirm the statement, Figure 7 and 8 show data received for the wheel in the course of earlier TsAGI study [5]. Figure 7 shows HQ ratings for two test pilots as a function of damping ratio (the values varied from ζ=0.3 up to 1.2). It is seen that despite of the fact the damping varied in a large range, the pilot ratings did not noticeably change. Figure 8 shows the percentage of forces due to damping referred to total manipulator forces. It is seen that, first, the contribution of damping is very small, and, second, it reduces with force gradient increase.

4. *Limb-manipulator open loop system.* The changing the neuromuscular system has a certain impact on limb-manipulator open-loop system magnitude. Figure 9 summarizes analysis of the limb-manipulator describing functions for different values of force gradient and shows cutoff frequency (ω_{lm}) as a function of the gradient. It is seen that there is a range of force gradients, both for the wheel and sidestick, in which the cutoff frequency remains constant. This range of force gradients coincide with that corresponding to the best handling qualities

ratings. This fact can be assumed an objective confirmation of the feel system optimality.

For the force gradients above the optimal range, the adaptive capabilities of the neuromuscular system reduce and the limb-manipulator cutoff frequency reduces as well. For the force gradients smaller than the optimal range, a pilot can apply greater gain and, thus, the cutoff frequency increases. But, at the same time, pilots do not like light-loaded manipulators due to reduced force feedback, which results in lower handling quality ratings.

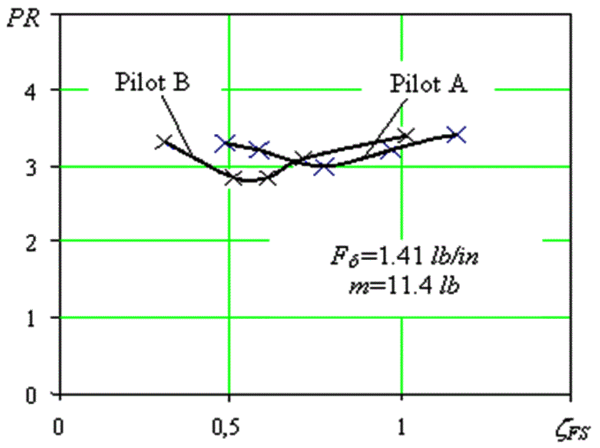

Fig. 7. Pilot ratings as a function of damping ratio (wheel, roll axis).

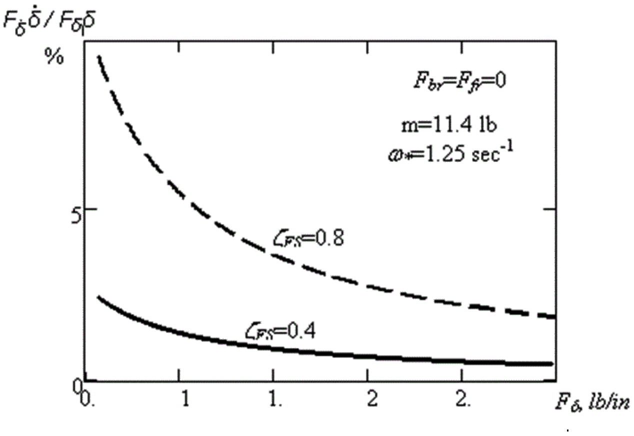

Fig. 8. Damping contribution to the total manipulator force (wheel, roll axis).

Figure 10 shows limb-manipulator cutoff frequency as a function of damping ratio for the sidestick. It is seen that as the damping increases above a certain value, the cutoff frequency remains constant. This fact confirms the statement above that the damping within the considered range does not lead to increase of manipulator total forces.

The value of damping, from which the cutoff frequency remains constant, can be assumed "minimum" value for the given force gradient, necessary to provide best handling qualities. For example, for force gradient Fδ=500 N/m (as shown in Fig.10) the "minimum" value of damping ratio is ζFS=1.0. The "maximum" damping value can be selected to prevent biodynamical interaction in pilot-aircraft system (high-frequency oscillations). The estimations of the maximum damping value for different manipulator types can be conducted according to the criterion developed in [5].

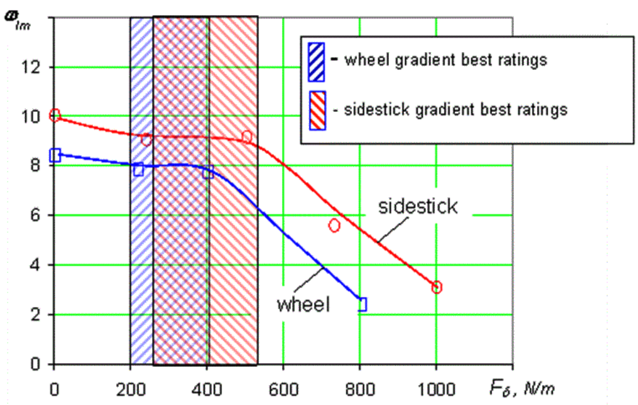

Fig. 9. Cutoff frequency of the limb-manipulator open-loop system as a function of force gradients for the wheel and sidestick.

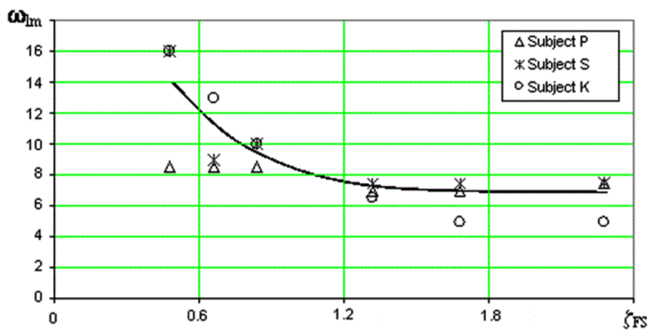

Fig. 10. Cutoff frequency of the limb-manipulator open-loop system as a function of damping ratio for a sidestick (F_δ=500 N/m).

4 Conclusions

The presented work is the first step of studying the effects of manipulator feel system characteristics on pilot model, and determining a criterion of feel system characteristics optimality. The results received are of regular nature and, thus, extend theoretical and practical aspects of pilot model use for handling quality assessment. The further works should be done to enlarge the experimental database received for the roll axis, and to conduct similar experiments for the pitch control axis.

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