Effect of Manipulator Feel System Characteristics on Pilot Frequency Response

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Abstract
Studied are the regularities of the effect of inceptor feel system characteristics (wheel, sidestick) on the describing functions of the pilot model its component: neuromuscular system, limb-manipulator system, central nervous system. The identification is made of the transfer functions for the considered components of the pilot model. The adequate identification of the transfer functions are confirmed by the good agreement of the estimations with the experimental describing functions.
The regularities of the effect of sidestick and wheel force gradient on neuromuscular gain and open-loop limb-manipulator cutoff frequency are analyzed. Determined is the range of neuromuscular parameters adjustment to force gradient variation. The received objective characteristics are in a good agreement with the subjective pilots' opinion on the optimum range of force gradients.

1. Introduction

It is well-known that a change in feel system characteristics affects the pilot control activities and pilot ratings considerably, being an evidence of the effect of the inceptor performance on pilot-aircraft dynamics.
A number of recent developments in aircraft design, such as lower frequency of oscillations due to structural elasticity (since modern aircraft are larger, but less heavy and more elastic), made it necessary to look into the effect of the limb-manipulator system on pilot-aircraft biodynamic interaction.
This means the limb-manipulator characteristics have to be studied in detail, with the stress on feel system characteristics interaction with the neuromuscular characteristics. Identification of pilot model parameters has been studied in detail as a while, while the effect of feel system characteristics on pilot describing function has not been sufficiently considered.
This work is to consider the interaction between pilot describing functions and feel system characteristics for various types of inceptors, namely , the interaction of the feel system characteristics with the central nervous system, the neuromuscular system, the limb-manipulator system and the pilot model as a whole.
The analysis procedure was as follows: first, the experimental data on each of the above-mentioned system frequency characteristics were analyzed; second, on the basis of the results, the structure of all transfer functions has been determined and substantiated; third, the best agreement of the estimated and experimental data transfer functions let us draw conclusions about the regularities in transfer function variation due to the differences in feel system characteristics.
If we have mathematical description of all pilot model components and all the regularities in transfer function variation, we are able to evaluate the effect of any feel system characteristics.

2. Setting the experiment

To study the interaction of the feel system characteristics with the pilot model and aircraft handling qualities we should choose the structure of the pilot-aircraft model to be able to consider separately the central nervous system and the neuromuscular system components, since their parameters are affected by feel system characteristics variation. These requirements are met by the pilot model, which consists of two loops, visual cues are put into the first, or outer, loop, while force signals are put into the inner loop through the inceptor loading system.
This approach to pilot model parameter identification was proposed and validated in [1]. Similar approach is used by other authors [2-3].

The pilot-aircraft model considered is presented in fig.1. It consists of the following subsystems:

Y_p - pilot model as a whole;
Y_c - aircraft model;
Y_{lm} - closed-loop limb-manipulator system model;
Y_{cns} - central nervous system model;
Y_{ns} - neuromuscular system model;
Y_{FS} -feel system model.

In the proposed pilot-aircraft model the pilot model parameters depend on central nervous system parameters, on the parameters of the limb-manipulator system, and on aircraft dynamics. As the aircraft dynamics remained the same in the majority of our experiments, we may consider the pilot model parameter to be only affected by central nervous and limb-manipulator system parameters.

The experiments were conducted on TsAGI's Flight Simulator FS-102. Two control inceptors were considered: wheel and sidesticks. The wheel and the sidesticks feel system characteristics were simulated by an electrical loading system (Moog) which allows wide variation of all static and dynamic wheel feel system characteristics.

Different inceptor feel system characteristics in roll were considered. In the majority of experiments force gradient variation was considered. To increase the reliability of the experimental data received, each simulated configuration was repeated 3 times.

In experiments we considered compensatory roll tracking task. In accordance with the diagram in fig.1, the pilot-aircraft system for this task includes the outer loop for tracking the input *i(t)* and the inner loop for manipulator positioning, the latter includes the second input *f(t)* (force disturbance) the pilot has to compensate while tracking. The pilot had to minimize the tracking error, which is the difference between the given *i* and output φ bank angles (fig.1). The tracking error was displayed at the main director.

To make describing function identification possible, inputs i(t) and f(t) were uncorrelated. The selected spectra of the inputs are shown in fig.2.

Three two-pilots participated in experiments.

The duration of each run was 210 seconds, the first 10 s were excluded from the data processing.

In the course of experiments time histories were registered, which were then processed by the identification program to receive the pilot model describing functions.

3 The effect of feel system characteristics on central nervous system parameters and limb-manipulator system parameters

Fig. 3-5 show the experimental frequency responses for central nervous, neuromuscular and limb-manipulator systems.

The neuromuscular system frequency responses can be described by the following transfer function:

$$Y_{ns}(s) = K_{ns} \cdot e^{-\tau_{ns}(s)} \frac{[T_{ns2}s+1]\cdot[T_{ns3}s+1]\cdot\left[s^2+2\varsigma_{ns}\omega_{ns}s+\omega_n^2\right]}{[T_{ns1}(j\omega)+1]\cdot\omega_{ns}^2} \qquad \textbf{(1)}$$

Where K_{ns} – gain coefficient, τ_{ns} - time delay, T_{ns1}, T_{ns2}, T_{ns3} - time constants for various neuromuscular system “inherent filters”, ω_{ns}, ζ_{ns} - neuromuscular system parameters.

This form of the transfer function is in agreement with those proposed in previous [2-4]; it accounts for the dynamics of the neuromuscular system, including the part of the central nervous system model where neural impulses originate from to actuate the hand and arm neuromuscular system.

Fig. 6 shows the comparison of the experimental frequency responses of neuromuscular system with calculated frequency responses based on (1) for the wheel and for the side stick. The agreement between the data for the two types of manipulators, both in amplitude and in phase, is clearly seen.

We are going to concentrate on the analysis of gain coefficient K_{ns} and limb-manipulator cutoff frequency ω_{lm}, since they are the major parameters affecting limb-manipulator dynamics.

3.1 Effect of force gradient

An increase in force gradient makes a pilot introduce greater force gain coefficient for the displacement to remain the same. The variation in force gain coefficient due to force gradient is shown in fig.7.

The neuromuscular system is adjusted to greater force gradient increasing its own gain coefficient for the inceptor displacements to remain the same. In the case of the sidestick, for gradients over 600N/m, the gain coefficient stops increasing, while in the case of the wheel even force gradients over 800N/m do not cause the increase of the gain coefficient. This may be accounted for by the difference in the limb force capability, on the one hand, and the single-handed control of the sidestick, on the other.
Fig.8 shows the cutoff frequency of the open-loop limb-manipulator system as a function of force gradient.
Greater gradient values correspond to lower cutoff frequency of the open loop limb-manipulator system, which means that the bandwidth of the limb-manipulator system becomes noticeably lower. The wheel force gradient from 200 to 400 N/m and the sidestick force gradient from 300 to 400 N/m correspond to the neuromuscular adjustment band, where the neuromuscular system can cope with the variation in the feel system characteristics for the bandwidth remain the same. In this case force gradient variation does not affect the limb-manipulator system bandwidth.
The experimental data in [5], show that variation in feel system characteristics leads to changes in pilot ratings. The data available [5] allow us to draw the conclusion that wheel force gradient variation from 200 to 400 N/m and sidestick force gradient variation from 300 to 650 N/m affects pilot ratings insignificantly (no more than 0.5). This conclusion agrees with the data received in the present work: within the above mentioned force gradient range the neuromuscular system parameters are easily adjusted for the force gradient variation. The aircraft handling quality within this neuromuscular adjustment range is rated as the best by the pilot.
If inceptor force gradients deviate from the optimum range, pilot ratings worsen. This pilot ratings worsening is confirmed by the changes in limb-manipulator system parameters. Fig.8 shows that as wheel force gradient increases over 400 N/m or decreases below 200 N/m the cutoff frequency of the open-loop limb-manipulator system does not hold constant, which is due to the fact the neuromuscular system is not within the adjustment range any more.
In the experiments conducted in the present work, the pilot rating worsening can be caused by the non-optimum control sensitivity as well, since the control sensitivity in the experiments was constant for the whole range of forces gradient variation. Thus, further experiments are needed to study the effect of feel system characteristics and control sensitivity on the adjusting capabilities of the neuromuscular system.
It should be mentioned that within the adjustment band the cutoff frequency for the sidestick is lower than for the wheel. In other words, in the case of sidestick, the bandwidth and accuracy of roll control cannot be as good as in the case of the wheel, which might be accounted for by limb physiological characteristics, on the one hand, and smaller sidestick displacements, on the other. Nevertheless, further studies are needed for the final conclusion on the matter.

4 Conclusions

1. Experimental describing functions are received for the pilot model and its components for different values of force gradients; two types of inceptors are considered: wheel and sidestick.
2. Identification are made of the transfer functions for the pilot model and its components: central nervous system, neuromuscular system, limb-manipulator system. The adequate identification of the transfer functions are confirmed by the good agreement of the estimations with the experimental describing functions.
3. The regularities of the effect of sidestick and wheel force gradient on neuromuscular gain and open-loop limb-manipulator cutoff frequency are analyzed.
4. Shown is that the open-loop limb-manipulator cutoff frequency can be an objective parameter determining the optimum values of force gradients. The received objective characteristics are in a good agreement with the subjective pilots' opinion on the optimum range of force gradients.

References

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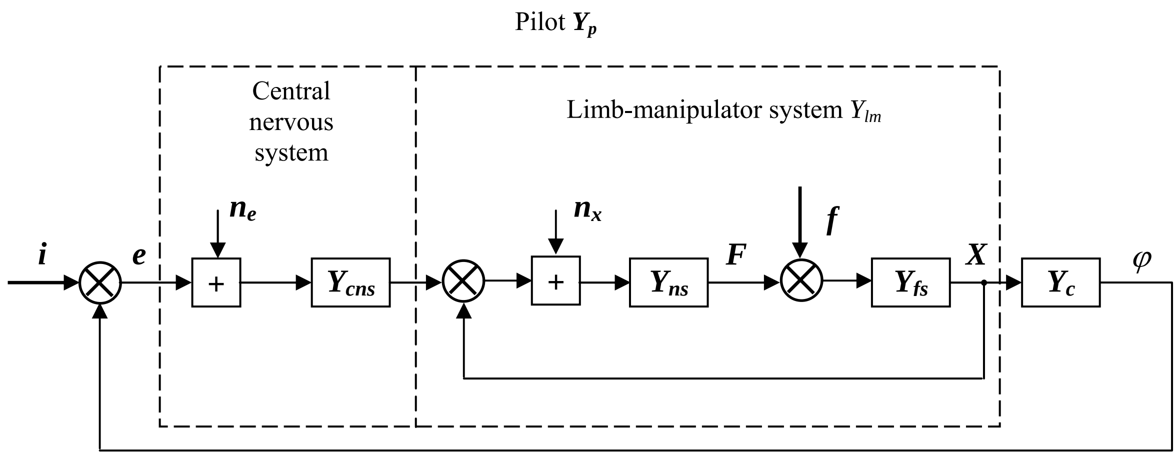
Figures



5.

Figure 1: The diagram of the pilot-aircraft model used in the analysis

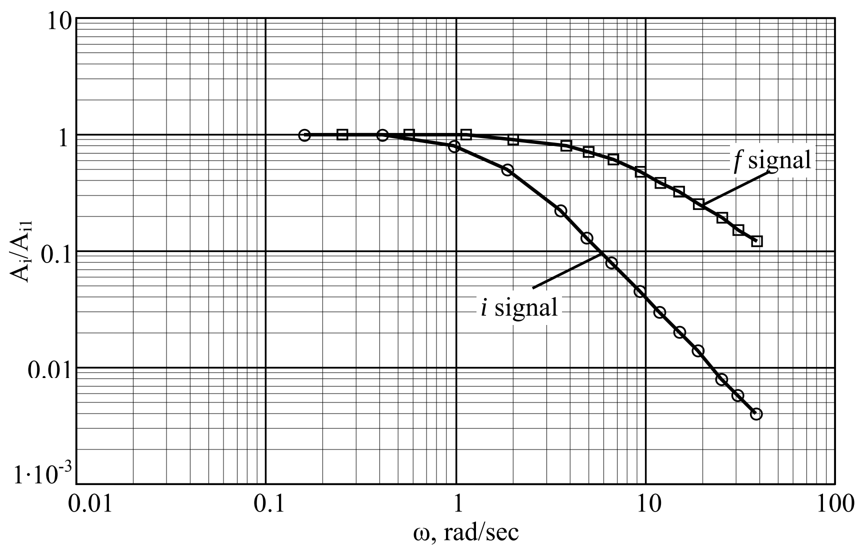


Figure 2: Inputs’ spectra

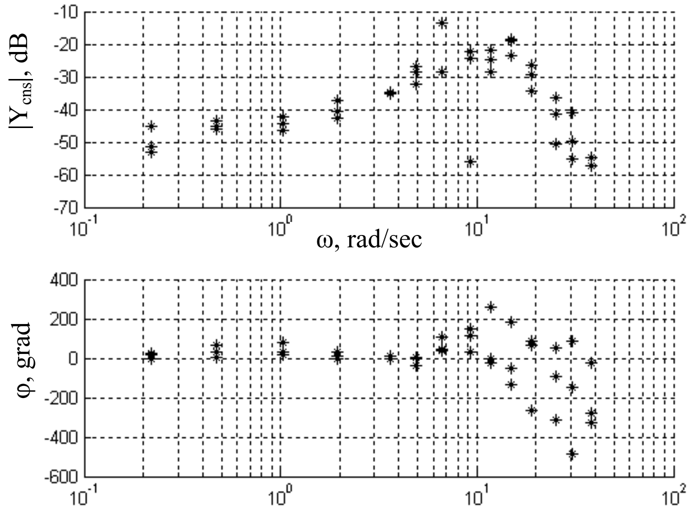


Figure 3: Frequency response for central nervous systems

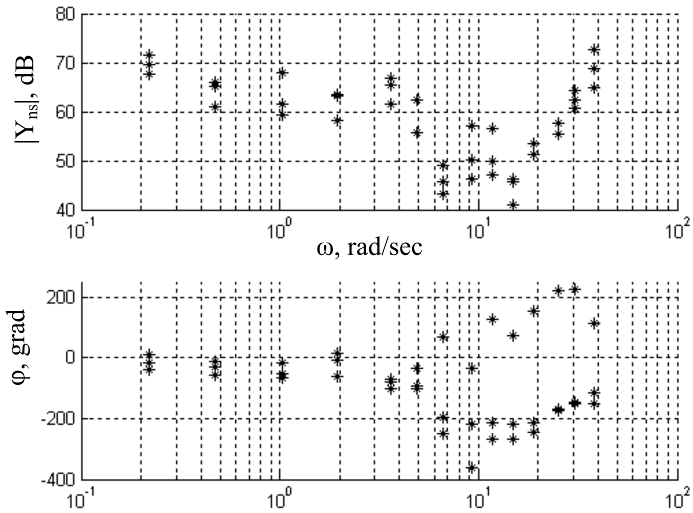


Figure 4: Frequency response for neuromuscular system.

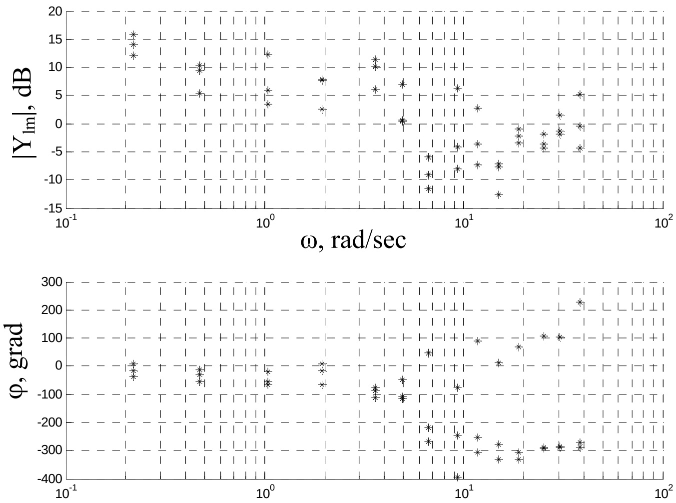


Figure 5: Frequency response open-loop limb-manipulator system.

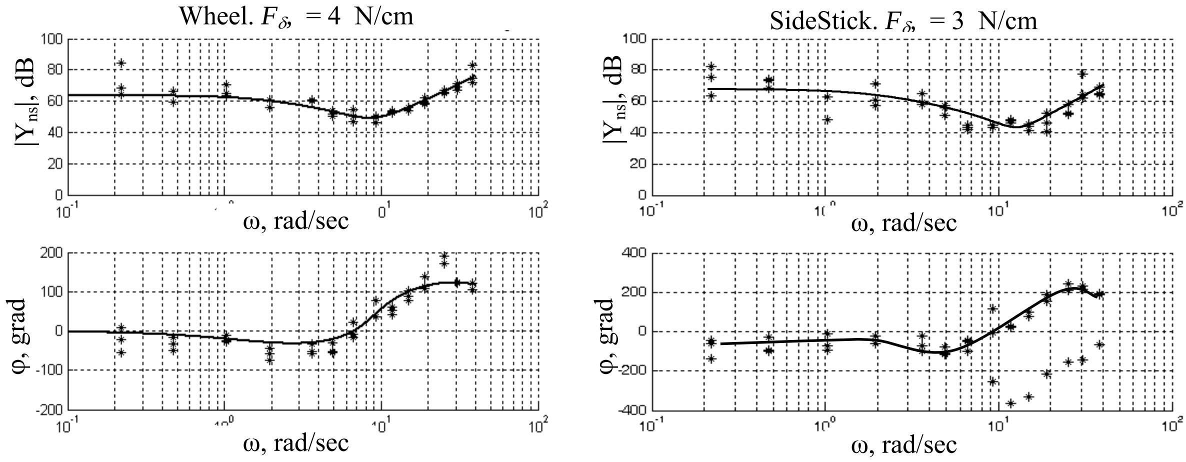


Figure 6: Comparison of the experimental frequency responses of neuromuscular system with calculated frequency responses based on (1) for the wheel and for the side stick.

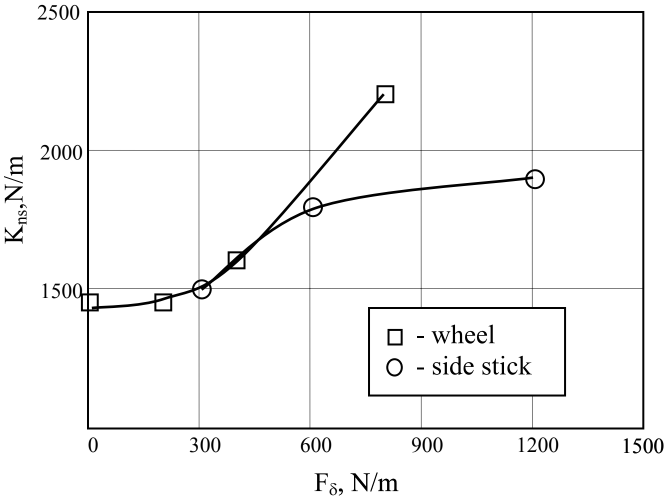


Figure 7: The variation in force gain coefficient due to force gradient.

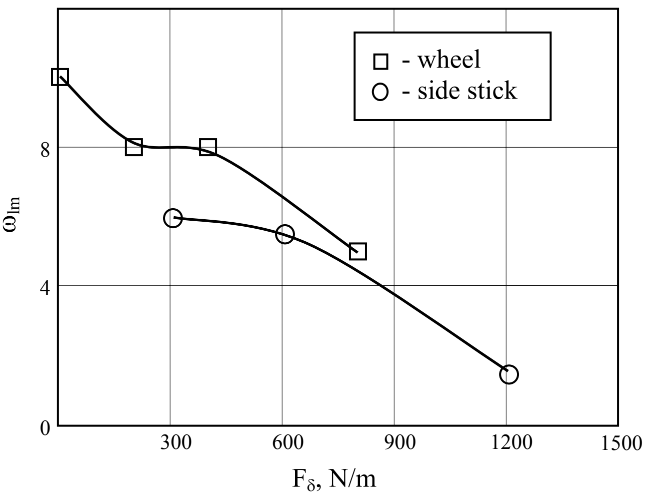


Figure 8: The cutoff frequency of the open-loop limb-manipulator system as a function of force gradient.