EFFECT OF MANIPULATOR TYPE AND FEEL SYSTEM CHARACTERISTICS ON HIGH-FREQUENCY BIODYNAMIC PILOT-AIRCRAFT INTERACTION

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Abstract

Results are presented of experimental research of mechanisms and characteristics of biodynamic interaction in pilot-aircraft system affected by high-frequency lateral accelerations.

Experiments were conducted in accordance with project ARISTOTEL funding from the European Community's Seventh Framework Programme.

In the experiments, different pilot-aircraft interaction loops were considered and their roles were assessed in terms of aircraft control and effect on high-frequency oscillations (PAO/APC) in pilot-aircraft system.

The effects of manipulator type (wheel, sidestick) and its feel system characteristics (force gradient, damping, friction, breakout force) were analyzed. It is shown that the characteristics have a considerable impact on the describing function of biodynamic interaction.

1 Introduction

There is a trend in aviation towards larger and lighter aircraft to accommodate the increase in global air traffic. The greater aero-elasticity effects may cause unfavorable aircraft-pilot couplings (APC), which can significantly affect the operational effectiveness of a given mission. Existing APC criteria do not take into account aircraft manipulator feel system characteristics and control sensitivity, although their effects can be considerable in this case.

In Russia, early investigations revealed that APC tendencies of flexible transport aircraft can be attributed to a resonant peak of the pilot's biodynamic feedthrough [1]. As previous experiments have shown, the frequency of resonant peak of limb-manipulator system depends on a manipulator type and its feel system characteristics. The range of resonance frequencies (1.5-3 Hz) are within the frequency range of structural elasticity. Their coincidence may cause noticeable oscillations in pilot-aircraft closed loop system through biodynamic feedback. Thus, there is a strong need to study pilot's biodynamic feedthrough in greater detail and to investigate the roles of manipulator feel system characteristics in pilot control activity. This study was the main goal of the presented work.

2 State of the problem

On the basis of a theoretical approach developed in TsAGI [2] to assess the effect of angular and linear accelerations and the analysis of the APC phenomenon mechanisms, described in [3,4,5], the integrated pilot-aircraft interaction in compensatory tracking task can be presented as it is shown in Figure 1.

In general, the block-diagram includes pilot model Y_p, aircraft model Y_c, visual input signal $i_{vis}(t)$, and feedbacks: informative feedback (on the controlled visual error e_v and acceleration a) and biodynamic feedback (acceleration force F_b).

Pilot model includes the model of central nervous system Y_{cns}, which produces the control signal u_c, and the model of limb-manipulator system Y_{lm} controlled by signal u_c.

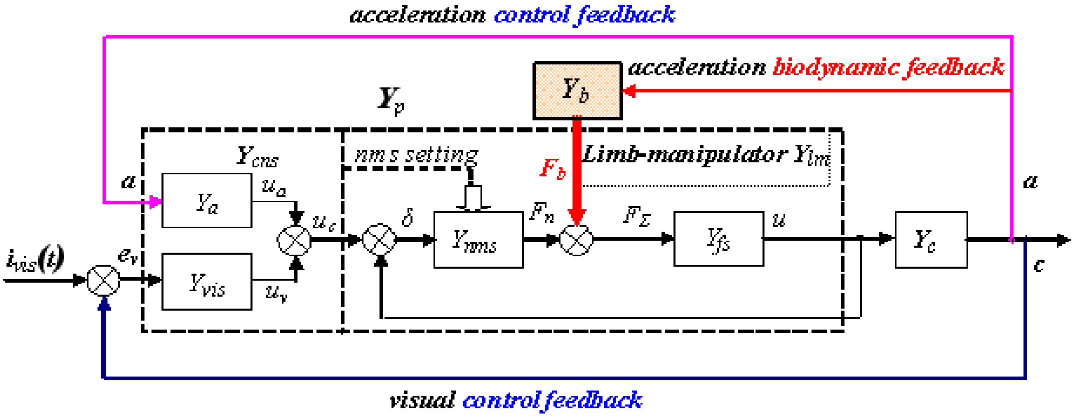

Fig. 1. Block-diagram of pilot-aircraft interaction loops.

The model Y_{cns} is the combination of Y_{vis}, which produces the control command u_v according to the visual error e_v, and Y_a, which produces the command u_a according to the accelerations a .

The limb-manipulator system, controlled by command u_c, is a combination of a the neuro-muscular system Y_{nms} and a manipulator with its feel system characteristics Y_{fs}. The limb-manipulator system has a feedback on the manipulator deflection u . In addition to the command signal u_c, there is an input F_b from the biodynamic interaction, which can arise due to unfavorable aircraft rigid-body dynamic characteristics or due to certain structural elasticity characteristics.

The block-diagram in Figure 1 simplifies theoretical and simulation analysis of different types of pilot-aircraft interaction. In general, it shows the operational activity of a pilot, who performs deliberate control actions in the compensatory tracking task in the presence of different informative feedback inputs (***visual and acceleration control feedbacks***) and unpleasant biodynamic accelerations (***biodynamic feedback***). The block-diagram can be used both to study the rigid-body and elastic-body pilot-aircraft interaction.

In the block-diagram, there is also the path *"nms settings"*. The path is not included into a closed-loop system, but can describe the changes in biodynamic interaction due to pilot control motivations [5].

If we ignore the ***control feedbacks***, we receive the block-diagram to study "passive" pilot behavior (Figure 2), when he/she does not perform deliberate control actions, but counteracts for the biodynamic force caused by accelerations. The involuntary body and limb displacements pass through the manipulator to the aircraft control system and amplify the accelerations.

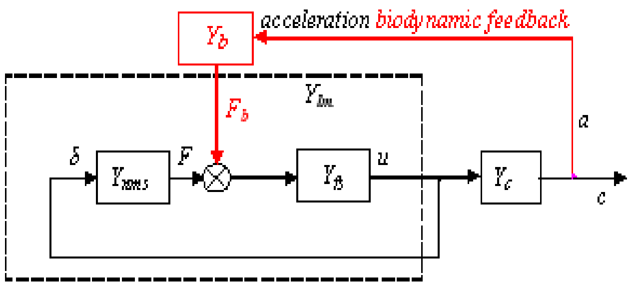

Fig. 2. Block-diagram of pilot-aircraft interaction for "passive" pilot in the loop.

Due to the fact the manipulator closes the loop of biodynamic interaction, its characteristics, i.e. type and feel system characteristics, can affect the biodynamic interaction intensity. The latter fact was confirmed in recent experiments [1]. Nevertheless, the majority of publications on the biodynamic interaction does not take into account the effect of manipulator feel system characteristics. Thus, the goal of the presented work was to study the effect of these characteristics on the pilot-aircraft biodynamic interaction (BDI). The study was performed for the roll control axis, since this is the axis, in which the BDI was observed more often [6].

3 Setting the Experiment

The TsAGI PSPK-102 6DoF Flight Simulator was used for this study. The general view of TsAGI hexapod ground-based flight simulator PSPK-102 is presented in Figure 3.

Figure 3: TsAGI's PSPK-102 Flight Simulator

The motion system consists of 6 actuators with hydrostatic bearings. The actuator's stroke is 1.8 m. The digital driving laws are used. The cycle time is 1 msec; 15-bit analog-to-digital and 13-bit digital-to-analog converters are used.

Fig. 4. View of PSPK-102 cockpit

To measure and register the accelerations reproduced, 6 acceleration transducers are placed in the simulator platform which allows measuring linear and angular accelerations along all degrees of freedom.

The simulator cabin is equipped with standard wheel/column controls, pedals and sidesticks (see Figure 4). All the controls are loaded by the electrical loading system of MOOG (ECoL-8000), which allows flexible changing of feel system characteristics. The manipulator forces were modeled in accordance with the following equation:

$$m\ddot{\delta} + F_{\dot{\delta}}\dot{\delta} + F_{\delta}\delta = F_{br}\,\mathrm{sgn}\delta + F_{fr}\,\mathrm{sgn}\dot{\delta} + F_p,$$

where: m is mass, $F_{\dot{\delta}}$ is damping coefficient, F_{δ} is force gradient, F_{br} is breakout force, F_{fr} is friction, F_p is pilot force.

The main goals of the experiment were to study the effect of the manipulator type and its feel system characteristics on biodynamical interaction of the passive pilot.

The diagram of the experimental setup is shown in the Figure 5.

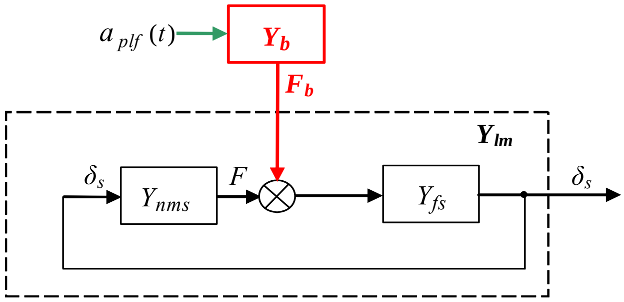

Fig. 5. Biodynamic experiment setup

The pilot (operator) had to hold the manipulator in a certain deflected position, controlling the position visually (the position of the manipulator was displayed).

The motion platform was moved in accordance with the following input signal:

$$a_{plf}(t) = \sum_{m=1}^{17} A_m \sin(\omega_m t + \varphi_m).$$

Parameters to vary were:

- manipulator types (sidestick, wheel);
- feel system characteristics $F_{\delta}, F_{\dot{\delta}}, F_{br}, F_{fr}$.

Recorded parameters are the signal from the acceleration sensor, manipulator position signal and manipulator force transducer signal.

In experiments, the describing functions of the biodynamic interaction δ_s / a were received. The describing functions were determined through cross and auto spectral density, which were calculated using fast Fourier transform (FFT):

$$\left\{\frac{\delta_s}{a}\right\}(j\omega) = \frac{S_{a-\delta_s}(j\omega)}{S_{a-a}(j\omega)}.$$

The time of each run was 50.96 sec. The frequency of signals recording was 100 Hz. The numbers of points considered were 4096 (first 10 sec were excluded because of the pilot (operator) adapted to the task).

4 Results and Discussion

The limb-manipulator system (see Figures 1,2) is an output of the pilot model, and its characteristics affect frequency responses of BDI. The input signal is the biodynamic force F_b .

Now we consider the effect of different feel system characteristics (force gradient, damping, friction and breakout force) on BDI characteristics. Since the feel forces counteract the involuntary displacement of the limb, an increase of forces leads to less biodynamic interaction, but the effect of feel characteristics is different.

4.1 Force Gradient

Figure 6 shows describing functions of biodynamic interaction for different values of sidestick force gradient. It is seen that the describing function of the involuntary limb displacements has inconsiderable peak at frequencies 1-1.2 *Hz* (due to low damping of the limb) and high peaking at frequencies 3 *Hz* . The increase of force gradient results in considerable amplitude decreasing at small and middle frequencies, which is due to the fact that the increasing forces counteract the involuntary limb displacements. At the same time, the changes in high-frequency peaking at 3 *Hz* is not so considerable due to simultaneous decreasing of feel system damping $\zeta_{fs} = \dfrac{F_{\dot{\delta}}}{2\sqrt{mF_{\delta_s}}}$ and, thus, the limb-manipulator system as a whole.

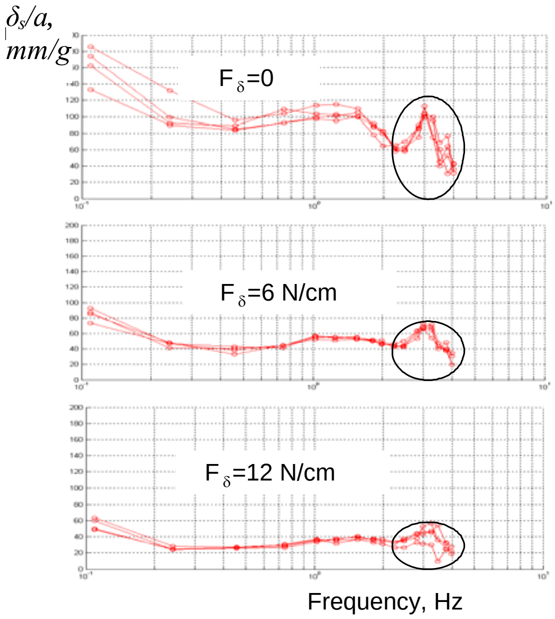

Fig.6 Influence of the feel system gradient on biodynamic feedthrough, $F_{\dot{\delta}} = 0$

The data presented allow us to conclude that force gradient increase alone cannot lead to noticeable decreasing of amplitude of involuntary limb displacements caused by structural elasticity accelerations with frequencies close to biodynamic resonance in body-limb-manipulator system.

4.2 Force of Damping

Figure 7 shows the effect of sidestick damping on the describing function of involuntary limb-manipulator system deflections. It is seen that as damping increases, the limb-manipulator displacements' amplitude decreases at all frequencies, the high frequencies included; at damping $F_{\dot{\delta}} > 0.5 N/sm/\sec$ the high-frequency peaking almost disappears. This fact is explained by reducing the tendency to oscillation (and, thus, amplitude) in the feel system and, thus, in limb-manipulator system as a whole.

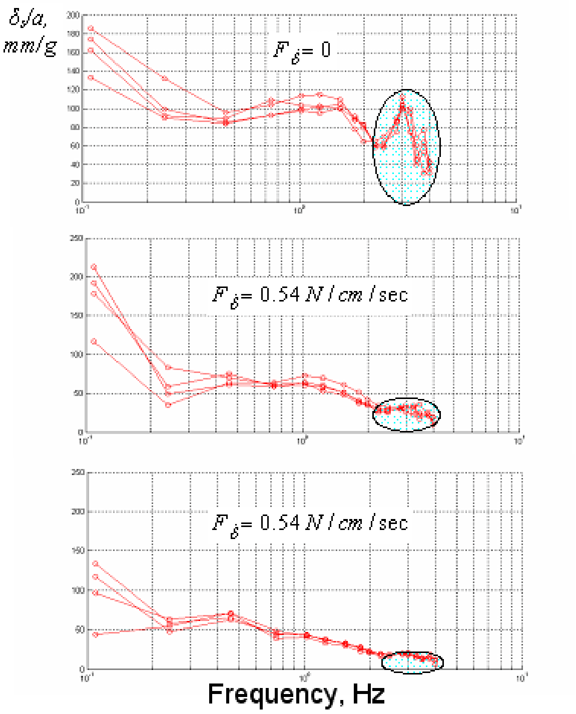

Fig.7 Influence of feel system damping on biodynamic feedthrough

It means that the damping to be added to feel system characteristics can be an effective method to reduce tendency to high-frequency oscillations caused by biodynamic interaction in body-limb-manipulator-aircraft system.

Nevertheless, it should be noticed that there is a certain optimum value of damping force [7] from point of view of aircraft handling qualities. The increase of damping above the optimum value can lead to worsen aircraft handling qualities. The manipulator is felt as too sluggish, which is negatively assessed by a pilot. Thus, the final selection of force damping should be made with due regard to these two factors.

4.3 Friction and Breakout Force

The experiments allowed estimation of the effect of nonlinear components of feel system characteristics (friction and breakout forces) on the BDI. Figure 8 shows BDI describing function for non-zero breakout force. The function, being compared to that in Figure 6, shows that the breakout force effect is somewhat equivalent to the force gradient effect: similar to force gradient, an increase of breakout force reduces the amplitude of involuntary limb-manipulator displacements at the small and middle frequencies; the high-frequency resonant peak is not affected considerably.

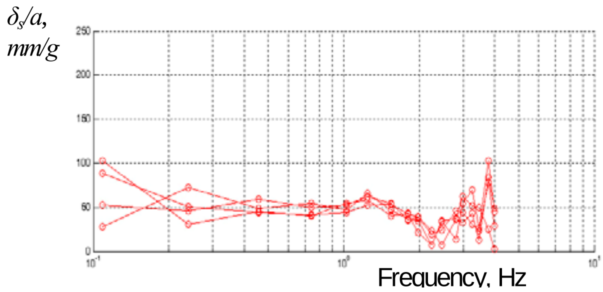

Fig.8 Influence of the breakout force on biodynamic feedthrough

The further increase of breakout force above the level of biodynamic forces can result in complete elimination of limb-manipulator involuntary deflections, but only if the manipulator is in the neutral position. But in reality, the BDI appears more often when the manipulator is deflected. Thus, the additional breakout force cannot be an effective method to reduce BDI.

Figure 9 shows the effect of friction on BDI.

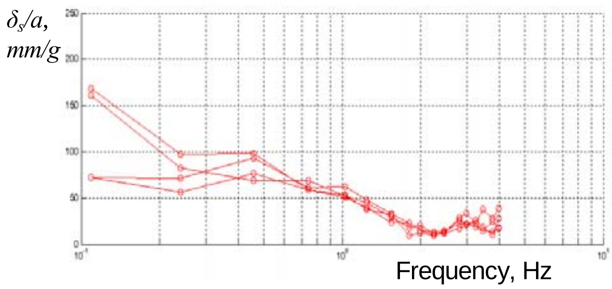

Fig.9. Influence of the friction on biodynamic feedthrough

Figure 9, being compared to Figure 7, shows that an increase of friction reduces high-frequency peak in BDI describing function. In other words, its effect is similar to the effect of damping. But, as experiments show, large friction value affects accuracy of pilot control activity, and thus, piloting accuracy and pilot rating. It means that the possibilities of feel system friction as an effective method to reduce BDI are very much limited.

The analysis allows us to conclude that the most effective method to reduce accelerations caused by aircraft structural elasticity and to prevent high-frequency BDI at the frequencies of structural elasticity is introduction of addition damping or force gradient.

Feel system characteristics of a manipulator are selected, first of all, from point of view of goo handling qualities. The feel system parameters are closely interconnected, and there are their optimum combinations, which depend on many factors [8]. Recently, a theoretical approach was developed and substantiated in TsAGI, which allows assessment and selection of feel system characteristics from point of view of aircraft handling qualities [8,9]. Taking into account the effect of feel system characteristics on BDI discussed in the present paper, the final selection of feel system characteristics should be made with due regard to these two factors.

4.4 Effect of Manipulator Type

To estimate the effect of manipulator type, two types of manipulators were considered in the experiments: a traditional wheel and a sidestick. The wheel and sidestick differ greatly from each other in their displacements (the wheel is 3 times greater than sidestick). In order to compare their effects on BDI, the data needs to be normalized, i.e. referred to the maximum values of, respectively, wheel and sidestick. Figure 10 presents the data for wheel and sidestick for force gradient equal F_δ=0.

It is seen that for the wheel the amplitude at high frequencies corresponding BDI is much less than that for the sidestick. For sidestick, the arm of the force due to biodynamic interaction is about 150 *mm*, and the force is applied by one hand; for the wheel, the force due to biodynamic interaction from one hand is compensated by the force from the other hand regardless of the wheel position.

This allows us to conclude that for the elastic aircraft equipped with traditional wheel the probability for BDI to arise and its intensity is much smaller than for the aircraft equipped with sidesticks.

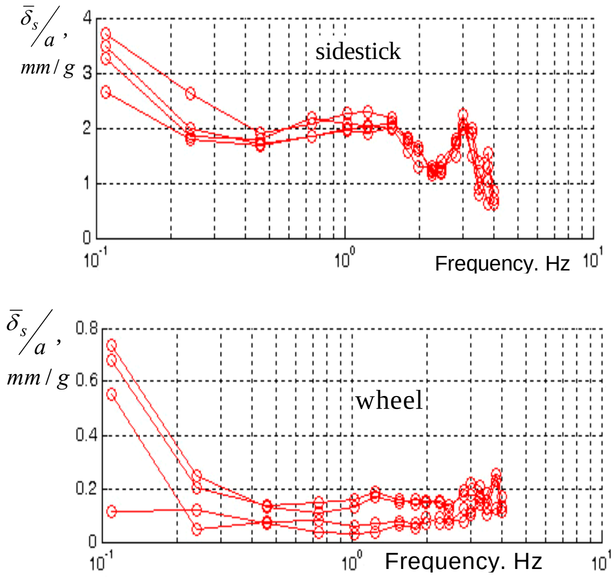

Fig.10 Influence of the manipulator type on biodynamic feedthrough

As experiments show, the effects of wheel feel system characteristics (force gradient, damping, breakout and friction force) on BDI are similar in kind to those shown for a sidestick, though in degree their effects are much smaller.

5. Conclusions

Simulator experiments were conducted to determine describing functions of the biodynamic interaction in pilot-aircraft system caused by lateral accelerations. The experiments were conducted for “passive pilot”, i.e. without any deliberate control actions from the pilot.

The experiments showed that the manipulator type and its feel system characteristics have great impact on biodynamic interaction. The sidestick and its characteristics affect BDI in greater extent than traditional wheel. In other words, aircraft with sidesticks is more prone to high-frequency oscillations due to structural elasticity that the aircraft with a wheel.

It is shown that the most effective method to reduce biodynamic interaction at high frequencies (2 *Hz* and above) is increasing of manipulator feel system damping. The force gradient is an effective method to reduce amplitude of the limb-manipulator involuntary displacements at small and middle frequencies (below 1 *Hz*).

Effect of breakout force on BDI is somewhat similar to the effect of force gradient; the effect of friction is similar to the effect damping.

The available theoretical approach developed in TsAGI to select feel system characteristics should be improved to take into account the peculiarities of the biodynamic interaction discussed in the present paper.

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