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AN APPROACH TO ASSESS AIRCRAFT – PILOT COUPLING CAUSED BY STRUCTURAL ELASTICITY

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Abstract

The approach is formulated to assess the effect of structural elasticity on aircraft handling quality as a function of structural elasticity and inceptor feel system characteristics. The analysis is performed which allows splitting the pilot activity into "active" component (active pilot) and "passive" component (biodynamical pilot). Received experimental database allowed identification of transfer functions of the pilot models and the rules of their parameter adjustment as functions of control inceptor type and feel system characteristics. A HQ criterion is developed to assess the effect of structural elasticity for aircraft equipped with inceptors of different types.

1 INTRODUCTION

This paper is about the European Commission 7th Framework Programme project ARISTOTEL[1]. [1–3].

According to the categories given in [4,5], the role of angular and linear accelerations arising in flight is dual: in some cases it is beneficial (accelerations are informative factor); in other cases it is negative (accelerations are negative factor). The high-frequency accelerations due to turbulence or those resulting from pilot activity due to inadequate aircraft characteristics can be attributed to the negative, or "biodynamical", factor.

Experiments conducted earlier showed, the frequency of resonant peak of limb-manipulator system depends on an inceptor 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 peaking in pilot-aircraft closed loop system through biodynamic feedback and lead to pilot rating worsening.

The high-frequency accelerations arising as a result of pilot activity can be subdivided into two groups: that ones which are caused by inadequate characteristics of *rigid-body* aircraft, and that ones which are caused by aircraft *structural elasticity*. For rigid-body aircraft, the authors of Ref.[6,7] proposed a theoretical approach to assess the effect of high-frequency accelerations arising during so-called rigid-body aircraft abrupt response (AR) to pilot activity. The high-frequency accelerations due to structural elasticity cause negative effect as well, since they lead to involuntary body and limb-manipulator system displacements, which interfere with pilot voluntary control activity (biodynamic interaction) and, finally, worsen handling quality ratings. Thus, it seems reasonable to apply the main idea of the theoretical approach stated in [6,7] to assess the effect of structural elasticity.

Thus, the goals of the present paper are:

- experimental study of the effect of manipulator feel system characteristics on handling qualities of aero-elastic aircraft;

[1] http://www.aristotel.progressima.eu/

- development of the criteria to assess the effect of structural elasticity.

2 MAIN PRINCIPLES OF THE APPROACH

2.1 Formulation of the Criterion

When a pilot controls an elastic aircraft (Figure 1), he, on the one hand, performs a piloting task, and, on the other hand, he is exposed to the disturbing high-frequency oscillations due to structural elasticity. In other words, pilot control activity (inceptor displacements) consists of two components: deliberately created by a pilot to control an aircraft, and involuntary inceptor displacements due to disturbing high-frequency structural oscillations. The two components can be described by different models corresponding to so-called "active" and "passive" (or "biodynamical") pilot models.

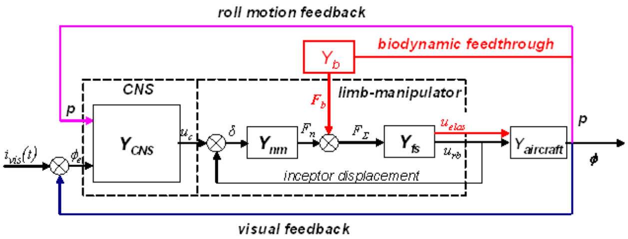

Figure 1. Block-diagram of pilot control activity for elastic aircraft.

The models have different inputs: for "active" pilot it is a visual signal; for "biodynamical" pilot it is high-frequency oscillations due to structural elasticity. The characteristic frequency ranges of the pilot models are also different: for the "active" pilot it is limited by 1.0-1.5 Hz; for the "biodynamical" pilot is above 1.5 Hz. Thus, in the first approximation, they can be considered independent.

It is natural to assume that the HQ pilot rating of elastic aircraft PR_Σ is a sum of the pilot rating of the rigid-body aircraft PR_{rb} and a certain pilot rating increment due to high-frequency elastic oscillations ΔPR:

$$PR_\Sigma = PR_{rb} + \Delta PR$$

It is natural to assume as well that the pilot rating increment ΔPR is a function of the level of high-frequency accelerations.

Similar to that for rigid-body aircraft [6,7], the pilot rating worsening due to high-frequency accelerations can be estimated as a function of parameter λ, which is a ratio between the high-frequency and low-frequency motion components. For the roll control axis, the ratio has the following form:

$$\lambda = \frac{\sigma_{n_y}}{\sigma_p}, \tag{1}$$

where σ_{ny} is root-mean square (RMS) of the lateral high-frequency accelerations (due to structural elasticity in our case); σ_p is RMS of the roll rates created by a pilot.

The reason to use (1) as a measure of the negative effect of high-frequency accelerations is that high-frequency accelerations are perceived by a pilot on the background of the low-frequency roll motion deliberately created to control an aircraft, which is confirmed by experimental data [5]. Thus, the worsening of aircraft handling qualities, caused by biodynamical effect of elastic oscillations, is determined by parameter λ:

$$\Delta PR = \Delta PR\ (\lambda). \tag{2}$$

2.2 Calculation of Parameter λ

Generally, pilot activities spectrum characteristics depend not only on the aircraft characteristics, but also on the piloting conditions: piloting task, urgency for high performance and turbulence. To estimate whether aircraft is prone to AR, it is natural to consider those piloting conditions, in which a pilot is more susceptible to the influence of lateral accelerations.

The effect of high-frequency accelerations is especially pronounced when no turbulence occurs and the pilot is not occupied by a piloting task, but manipulates the stick at will to evaluate HQ in an open loop. That is why the diagram to calculate parameter λ is the pilot-aircraft open-loop model.

To calculate RMS of the lateral accelerations (σ_{ny}) and roll rates (σ_p) in (1), we use random function theory. Assuming the pilot control activity is a stationary random process, the models of the active and biodynamical pilots can be presented as white noise passing through the corresponding filters, as it is shown in Figure 2. For the active pilot model, it is a filter, which reflects pilot activity to control aircraft in roll; for the biodynamical pilot model, it is a filter, which describes pilot' involuntary control activity caused by high-frequency lateral accelerations.

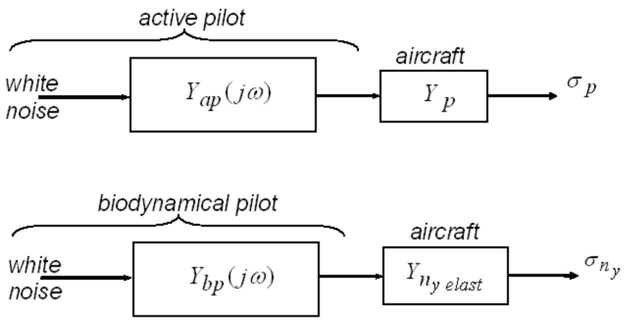

Figure 2. The models to calculate σ_{ny} and σ_p.

In this case, the values of σ_{ny} and σ_p can be calculated as follows:

$$\sigma_{n_y}^2 = \frac{1}{2\pi} \cdot \int_{-\infty}^{+\infty} \left| Y_{n_y}(j\omega) \cdot Y_{bp}(j\omega) \right|^2 d\omega \,,$$

$$\sigma_p^2 = \frac{1}{2\pi} \cdot \int_{-\infty}^{+\infty} \left| Y_p(j\omega) \cdot Y_{ap}(j\omega) \right|^2 d\omega \,, \qquad (3)$$

where Y_{ny} is aircraft transfer function for lateral accelerations; Y_p is transfer function for roll rate; Y_{ap} is transfer function for the "active" pilot; Y_{bp} is transfer function for the "biodynamical" pilot.

3 IDENTIFICATION OF PILOT MODELS

To use (2) for the assessment of the effect of structural elasticity and inceptor characteristics, we need to know transfer functions of the "active" and "biodynamical" pilot models in (3). The selection and identification of the transfer functions was performed on the basis of experimental data described below.

3.1 "Active" Pilot Model

To select and identify the transfer function for the "active" pilot we need, first of all, to determine the factors affecting the model. For this, series of experiments were conducted.

1. Effect of accelerations. Experiments were conducted in flight simulator PSPK-102 of TsAGI (in greater detail, the description of experiment is given in Chapter 4.1). The aircraft model was a model of generic aircraft with 3-mode structural elasticity (1.5 Hz, 2.5 Hz and 3.5 Hz). Experiments were conducted with and without platform motion. The pilots performed roll compensatory tracking task; a wheel was used as a control inceptor.

An example of pilot describing functions calculated using Fast Fourier Transform is presented in Figure 3. It is seen that the platform motion does not noticeably affect the describing function, in particular in the frequency range, typical of pilot control activities (up to 1.5 Hz).

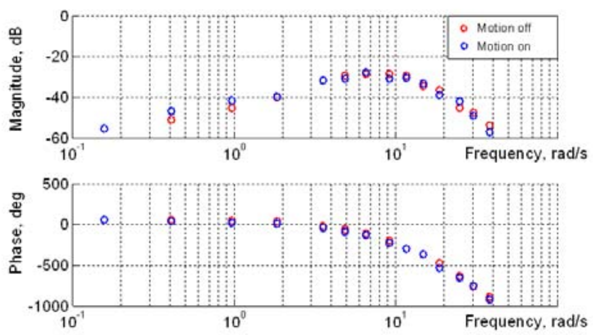

Figure 3. Active pilot describing functions demonstrating effect of high-frequency lateral accelerations

2. Effect of feel system characteristics. Experiments were conducted on flight simulators of TsAGI (PSPK-102) and NLR (GRACE). The aircraft model was a model of generic aircraft. The pilots performed roll compensatory tracking task.

Three types of control inceptors were considered: traditional wheel, sidestick and center stick. All the inceptors were loaded by the electrical loading system, which allows flexible changing of feel system characteristics. The manipulator forces were modeled in accordance with the following equation:

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

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

The pilot describing functions received for center and side stick for different values of inceptor force gradient and damping are shown in Figures 4 and 5.

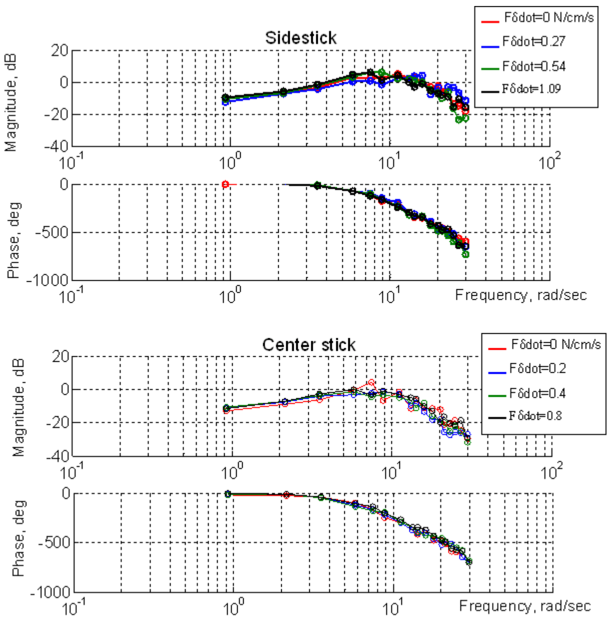

Figure 4. Effect of inceptor damping on the describing functions of the active pilot model.

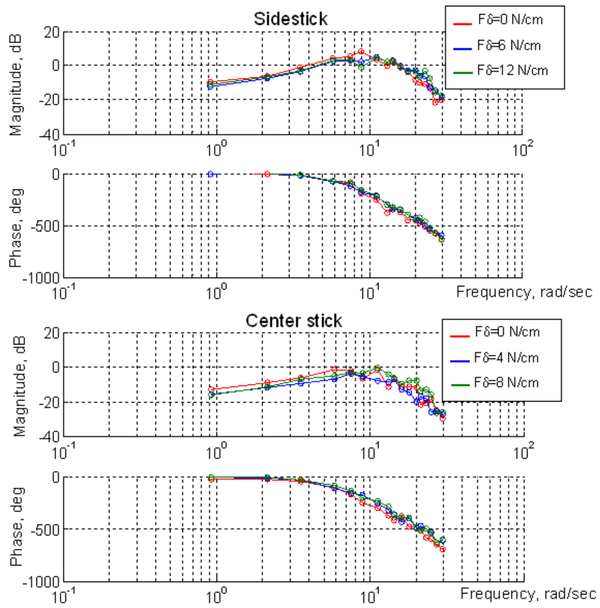

Figure 5. Effect of inceptor force gradeint on the describing functions of the active pilot model.

It is seen that the model of the active pilot does not practically depend on inceptor feel system characteristics, at least within the frequencies typical of pilot control activity (up to 1 Hz).

3. Effect of control sensitivity.

The active pilot model is a model, which describes pilot activity within the frequency range typical of piloting. It is known that within this frequency range a pilot can adjust his gain in accordance with the aircraft gain. This inherent property of a pilot is illustrated in Figure 6.

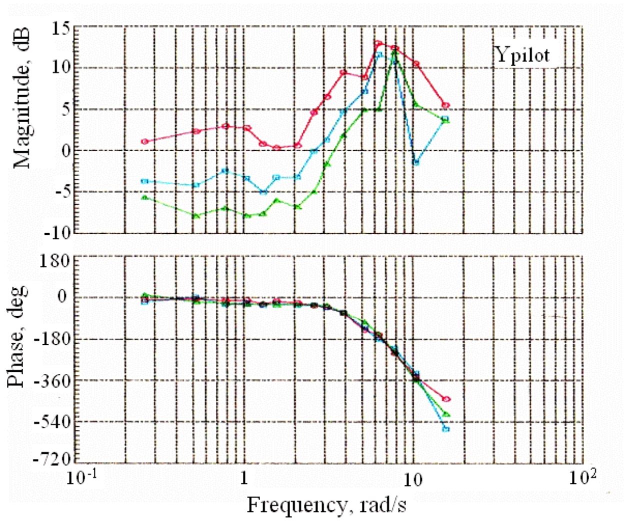

Figure 6. Effect of control sensitivity on active pilot model.

It is seen that as aircraft gain (control sensitivity) increases by factor K, a pilot changes his gain correspondingly by factor $1/K$ in order to make pilot-aircraft system cutoff frequency constant. At the same time, the amplitudes of the active pilot frequency response at the frequencies higher than 1 Hz are almost the same for different aircraft gains. The pilot model phase remains one and the same for different aircraft gains within the whole frequency range considered.

Thus, the only factor, which has any noticeable impact on active pilot describing function, is the aircraft control sensitivity. To take this into account, we can use the following filter to describe the active pilot activity:

$$Y_{act\text{-}pilot} = \frac{1}{s + \omega_* \cdot K / K_*} \qquad (4)$$

where K is an aircraft gain (control sensitivity) in the roll rate transfer function; K_* is a certain constant, which can be interpreted as a “characteristic” value of the gain K; ω_* =1 rad/s. Parameter ω_* is to provide identical dimension in the denominator of the formula.

In the control systems, which are controlled by inceptor displacements, the value of control sensitivity depends on inceptor type and its travel capabilities. For example, for a sidestick, which displacements are 3 times less than for the wheel, the optimum value of control sensitivity is approximately 3 times less than that for the wheel. This enables us to assume that the value of the “characteristic” gain K_* depends on inceptor type in the same proportion as the optimum control sensitivity.

3.2 “Biodynamical” Pilot Model

The involuntary body and limb displacements pass through the manipulator to the aircraft control system and can amplify the high-frequency accelerations. Due to the fact the inceptor is in the closed loop of biodynamic interaction (Figure 1), its feel system characteristics can affect the biodynamic interaction (BDI).

To identify the “biodynamical” pilot model and to study the factors which can affect the model, special biodynamic tests were conducted on flight simulators TsAGI (PSPK-102) and NLR (GRACE). The human pilots were instructed to keep the inceptor in the vicinity of the reference position in presence of lateral accelerations produced by flight simulator motion system.

As it was stated in previous publications (see, for example, [8]), within a limited range of friction and breakout forces variation, the effect of breakout force on BDFT is somewhat similar to the effect of force gradient, and the effect of friction is similar to the effect of damping. Thus, we pay here the greater attention to the effect of force gradient and damping.

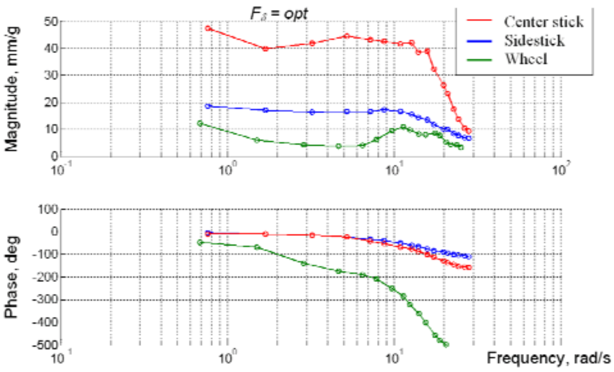

Figure 7. Comparison of the BDI for different types of control inceptors.

Figure 7 presents experimental results on biodynamic interaction for different types of manipulators, their feel system characteristics being optimum. Figure 8 presents effect of force gradient and damping for the sidestick.

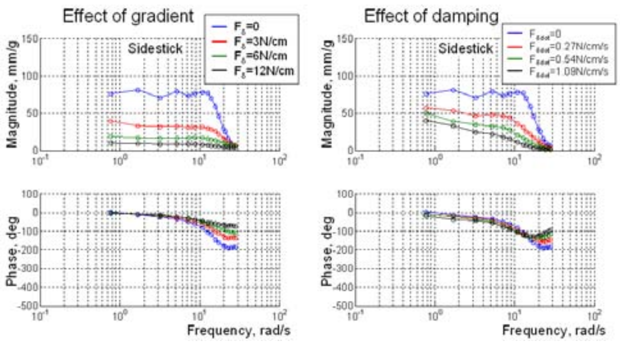

Figure 8. Effect force gradient and damping on BDI for the sidestick.

Analysis of this and other data can be summarized as follows:

- biodynamical interaction (biodynamical pilot model) depends on inceptor type: the smallest BDI is observed for the wheel;
- force gradient increase leads to BDI diminishing, but its variation may result in rigid-body handling quality worsening
- inceptor damping is the most effective method to suppress biodynamical interaction, since it considerably reduces the high-frequency inceptor oscillations, and, at the same time, does not cause pilot ratings deterioration in a wide range of its variation.

Comparison of the calculated and experimental describing functions showed that their adequate agreement is achieved if we use the following transfer function:

$$Y_{bp}(s) = K \cdot \left(\frac{Ts+1}{T_l s+1}\right) \cdot \left[\frac{1}{T_1^2 s^2 + 2T_1\zeta_1 s + 1}\right] \quad (5)$$

The parameters in (5) depend on the type of inceptor: the force gradient increase results in decreasing gain K only; the variation of inceptor damping leads to variation of parameters T_1 and ζ_1 for a sidestick, and T and ζ_1 for a center stick. In greater detail, the results and the parameter adjustment rules are presented in [9].

Assessment of the biodynamical interaction intensity should be made in terms of "caused harm", or, in other words, in aircraft lateral accelerations, which can be exited by the involuntary pilot control activities: the greater inceptor displacements, the greater the exited accelerations. Taking into account the fact the control sensitivity is selected as a function of inceptor maximum displacements, the gain K in (5) must be normalized with the inceptor maximum displacements. Thus, we have:

- for the center and side sticks K=0.4;
- for the wheel K=0.06.

It means that in case of biodynamic interaction in the pilot-aircraft system, the aircraft with a wheel would have 7 times as much less accelerations than aircraft with a center or side stick. It should be mentioned that this conclusion is true only if the control sensitivity and inceptor feel system characteristics are selected optimum.

The adjustment rules for the coefficients in (5) for the center, side sticks and the wheel are presented in the Tables below as a function of inceptor damping, provided force gradients are optimum. Since the pilot-aircraft system with a wheel is practically not prone to the BDI, the coefficients in (5) for the wheel can be assumed constant regardless of the wheel damping.

	P^{xdot}=0	**0.27**	**0.545**	**1.09**
***T*, s**	0.4	0.4	0.4	0.4
T_l, s	0.5	0.5	0.5	0.5
T_1, s	0.065	0.08	0.09	0.13
ζ_1,	0.5	0.6	0.7	0.8

Table 1. Coefficients in (5) for the sidestick.

	P^{xdot}=0	**0.2**	**0.4**	**0.8**
***T*, s**	1.2	1.0	0.9	0.8
T_l, s	1.2	1.2	1.2	1.2
T_1, s	0.06	0.06	0.06	0.06
ζ_1	0.6	0.8	0.9	1.2

Table 2. Coefficients in (5) for the center stick.

	P^{xdot}=var
***T*, s**	1.3
***T_l*, s**	1.2
***T_1*, s**	0.06
ζ_1	1.2

Table 3. Coefficients in (5) for the wheel.

Figure 9 shows comparison of the experimental data and calculations according to (5) for different inceptor types and corresponding parameter adjusting rules.

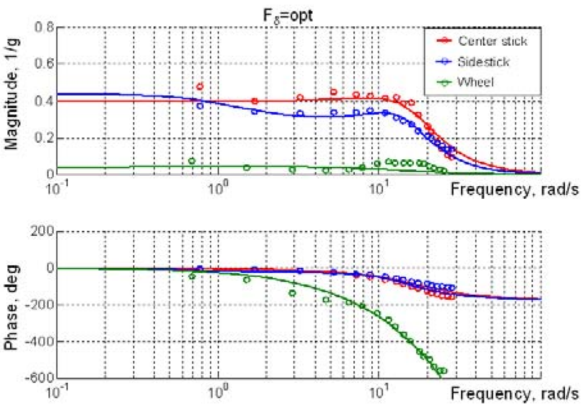

Figure 9. Comparison of the experiments and calculations. Different types of control inceptors.

The good agreement between the calculation and experiment enables us to use transfer function (5) in expression (3) to calculate the RMS of lateral accelerations caused by structural elasticity and inceptor feel system characteristics.

4 VALIDATION OF THE CRITERION

4.1 Setup of Experiments

The main goals of the experiments are: (1) to assess the effect of aircraft structural elasticity on pilot rating increment; (2) to assess the effect of inceptor feel system characteristics on the pilot ratings of the elastic aircraft.

To determine the effects and to validate function (2), experiments were conducted on flight simulator PSPK-102 (TsAGI).

The aircraft model was a model of generic transport aircraft with 3-mode structural elasticity (1.5 Hz, 2.5 Hz and 3.5 Hz). The model was developed to assess all factors affecting biodynamic pilot-aircraft interaction: structural elasticity mode frequencies and amplitudes, rigid-body control sensitivity, and inceptor feel system characteristics. Traditional wheel and sidestick were considered as the main control inceptors used nowadays in the modern airliners.

The research program included two series of experiments:

I. To determine the effect of structural elasticity and rigid-body control sensitivity (for each type of inceptor and its feel system characteristics as invariant).
II. To determine the effect of inceptor type and its feel system characteristics (structural elasticity characteristics as invariant).

In the second series, only inceptor damping was varied, as the most effective parameter in terms of BDI.

The BDI is the most demonstrative when pilots perform abrupt control inputs provoking high-frequency elastic oscillations and subsequent biodynamical pilot-aircraft interaction. Taking this fact into account, the following piloting tasks were selected:

1. Gust landing. Initial conditions: altitude 262 *ft*, heading 0, distance from the runway 0.81 miles. At 115 *ft* altitude a side step-wise left or right (random) wind gust is introduced, which leads to aircraft rolling and lateral drifting. To compensate for the aircraft motion, a pilot should respond quickly to align the aircraft along the runway avoiding large bank angles.
2. Tracking the “jumping” runway. The initial altitude is 50 *ft*, heading and bank angle are zero. In the course of experiment the runway right- and left-side shifting is simulated in turns every 20 seconds. The size of shifting is equal to the half-size of runway 98 *ft*. The pilot is to align aircraft along the runway centerline after every runway “jump”.
3. Roll tracking task. The pilot is to compensate for the tracking error, indicated on the head-up display as a moving bar. The visual input is a sum of sines.

Three experienced pilots participated in experiments.

After a pilot performs all piloting tasks for the considered configuration, he gives a final pilot rating of aircraft handling quality both for the rigid-body and elastic-body aircraft configurations.

The pilot rating increment ΔPR is determined as the difference between the pilot ratings given for the elastic aircraft and rigid-body aircraft for the same control sensitivity characteristics and inceptor feel system characteristics. To approach the common regularities, ΔPR received for all pilots were averaged.

4.2 Analysis of Experimental Data

Experimental data, received for the wheel and sidesticks for the same structural elasticity characteristics and optimum inceptor feel system and control sensitivity characteristics, shows that pilot rating increments are almost equal for the wheel and sidestick. In other words, the type of inceptor does not affect pilot ratings of elastic aircraft HQ.

This fact allows us to assume coefficient K in transfer function (5) equal 1 to calculate σ_{ny} for all types of control inceptors (if force gradient is selected optimum).

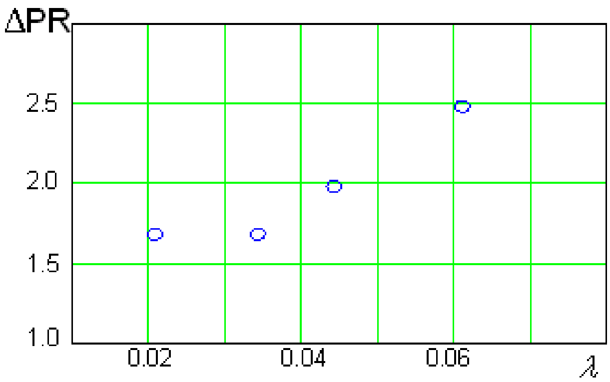

Figure 10. Effect of sidestick damping on pilot rating of elastic aircraft HQ.

Figure 10 shows experimental data received for the sidestick with different values of damping for one and the same characteristics of structural elasticity. It is seen that the damping increase can result in a certain pilot rating improvement. The degree of pilot rating improvement depends, apparently, on the structural elasticity characteristics. To make more valid conclusion on the effect of sidestick damping, greater statistics are needed.

All experimental data received in the course of the experiments are shown in Figure 11 (the data on the effect of sidestick damping is shown with blue circles).

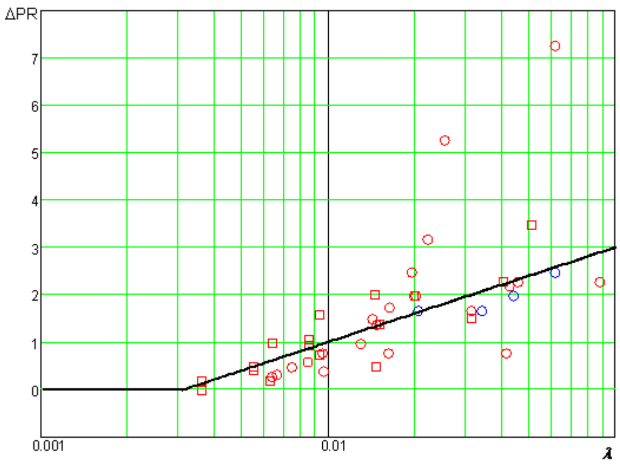

Figure 11. Empirical criterion to assess the effect of structural elasticity on pilot rating worsening.

The boxes are the data received for the wheel; the circles are the data received for the sidestick. It is seen that all the data are located along a line, which can be approximated by the following function:

$$\Delta PR = 2.0\, lg\, \lambda + 5.0 \quad (\text{at } \lambda \geq 0.003)$$

The good agreement of the experimental and calculated data validates the criterion and the models used to calculate parameter λ.

5 CONCLUSIONS

The study conducted in the work allows us to make following conclusions:

- For the systems with a wheel, the intensity of the biodynamic interaction in the pilot-aircraft system is considerably (7 times as much) less than that for the systems with sidesticks and center stick. For the center and side sticks the intensity of the BDI is approximately equal.
- Inceptor damping is the most effective method to suppress biodynamical interaction, since it considerably reduces the high-frequency inceptor oscillations, and, at the same time, does not cause pilot ratings deterioration in a wide range of its variation.
- Pilot ratings worsening is determined by the biodynamic effect of lateral accelerations due to structural elasticity. For the systems with sidesticks the effect can be diminished by introducing a certain damping.
- The developed criteria can be used to assess pilot rating worsening due to structural elasticity characteristics and with regard to inceptor feel system characteristics.

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