Handling Qualities of Transport Aircraft Equipped with Sidesticks

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Abstract

Studied are aircraft handling qualities in the case of sidestick control. Analyzed are the factors determining handling qualities and sidestick control advantages and disadvantages in comparison with other inceptor control (central stick, column/wheel).
Presented are the simulator experimental results to develop the requirements to aircraft handling qualities for the case of sidestick control. The experimental data and the theoretical approach proposed are the basis for the amendments proposed for the Standards to feel system characteristics and aircraft control sensitivity in pitch and roll control of an aircraft with sidesticks.
The interaction of two pilots while sidesticks control has been studied. The experimental data show that "active" sidesticks with mechanical linkage simulation have advantage over "passive" sidesticks without mechanical linkage. Given are proposals concerning active operational functions to improve aircraft handling qualities and flight safety.

Introduction

Widely used fly-by-wire flight control systems on modern transport aircraft have determined the tendency to replace traditional control inceptors (column/wheel, central stick) with a smaller manipulator, namely, a sidestick, which has a number of advantages: improved ergonomics of the cockpit, a better view of the instrumentation desk, less physical workload on a pilot, better dynamic characteristics of "pilot-manipulator-control system-aircraft" loop. These advantages have been decisive while developing a family of Airbus airliners and Russian "SSJ-100" equipped with sidesticks.
Nevertheless, in spite of some experience in developing and operating aircraft with sidesticks, some issues in the field of handling qualities are still unclear. So far, the Standards do not include any numerical requirements to control sensitivity and feel system characteristics of sidesticks and are limited to the general requirements that "the sidestick force should not be undesirable to the pilot"[1-3]. Thus, all current feel system characteristics and control sensitivity values are selected on the general grounds such as human physical capability to control with an inceptor located to the left or to the right of the pilot.
Even in aircraft with wheel or central stick control difficulties and uncertainty in selecting feel system characteristics and aircraft control sensitivity are determined by complex interaction of the characteristics and by their dependency on aircraft dynamic performance. To correctly select feel system and control sensitivity characteristics and to reduce the number of inevitable experiments, an analytical method has to be developed. Such a method has been developed in TsAGI [4-6] and successfully applied to various aircraft developing, including those equipped with non-traditional control inceptors (Tupolev-204, 334). Thus, it would be reasonable to use the method to select the control sensitivity and feel system characteristics of aircraft with sidestick control too.
While developing sidestick flight control systems a special attention is paid to safety and control reliability in general, and, in particular, to interaction of two pilots in the case of sidesticks without mechanical linkage. The so-called "active" sidesticks have been recently developed allowing to simulate sidesticks mechanical linkage and to supply tactile

information on the approaching critical flight modes, and to fulfill some other operational functions. The present work includes the experimental data on the efficiency of sidestick control.

1. Distinctive features of sidestick control

The main advantage of the sidestick is improved ergonomics of the cockpit, a better view of the instrumentation desk, less physical workload on a pilot, which has determined the popularity of sidesticks as an alternative to other inceptors.
Another advantage of a sidestick is seen if we consider pilot control dynamics. Figure 1 shows the experimental results to identify pilot dynamic characteristics for a pitch tracking task. The figure shows that sidestick control leads to decrease in pure time delay, as compared to traditional inceptors, which allows greater gain coefficient in the open-loop pilot-aircraft system and, as a result, wider bandwidth [7]. This is accounted for by less inertia of sidesticks and greater mobility of limb muscles engaged in operating the sidesticks in pitch. Thus, in pitch the piloting accuracy of a sidestick-controlled aircraft may be the same or better than that of a wheel-controlled aircraft (fig.2) [7-8].
The experiments have shown that in roll control the piloting accuracy of a sidestick-controlled aircraft nay be worse than that of a wheel-controlled aircraft (fig.3). Generally, pilots had a favorable opinion of sidestick control, but the flight tests have shown a certain tendency to PIO in roll while landing approach, which did not occur on wheel-controlled aircraft [9].
The analysis of the reasons for those phenomena and experiments have led us to conclusion that the PIO tendency is due to less shaping accuracy in the case of sidestick control, which is shown in figure 4, where experimental data are presented on shaping accuracy for sidestick, central stick and wheel over the whole range of their deflections. It is seen that the best shaping accuracy is observed in the case of wheel control, and the worst shaping accuracy occurs in the case of sidestick control, which is especially prominent in roll control (three times worse than for the wheel). This means that in sidestick control a pilot has to perform a considerably greater number of correcting movements which lead to aircraft oscillations, especially while approach and landing when roll accuracy is essential.
Poorer shaping accuracy in sidestick control affects aircraft handling qualities as well. Smaller displacements and forces in sidestick control and, as a result, smaller displacement and forces levels to create a unit of acceleration (δ_{nz},F_{nz}) and roll rate (δ_{ap},F_{ap}) make it difficult the selection of control sensitivity to exclude PIO tendency. Besides, the control sensitivity depends on feel system characteristics and both should be selected for handling qualities to be optimum.
Another problem is aircraft with “passive” sidesticks without mechanical linkage, which calls for new approach to the pilots’ interaction, in critical situation especially. In this case, each of the pilots perceives the other pilot’s activity through the aircraft response only, which means inevitable delay in his own response to inadequate piloting of the other. Without mechanical linkage student pilots cannot be instructed by following the instructor activities.
Thus, the distinctive feature of sidestick control can be seen while developing aircraft control system, selecting sidestick characteristics and ensuring the desirable handling qualities.

2. Feel system and control sensitivity characteristics

It has been shown that acceptable handling qualities can be ensured if control sensitivity is optimum or near optimum, which depends on the type of the inceptor, its feel system characteristics, aircraft dynamics, control axis and flight mode [6,10]. D.R.McRuer wrote in [11]“…the proper setting of controlled element gain has become *a non- trivial* development aspect on every new aircraft that introduces *a new inceptor*. In the absence of an extensive background of data for these there is no basis other than experiment to determine the optimum gains.” For aircraft with sidesticks, the lack of experimental database and estimation criteria to assess the above mentioned characteristics presents a serious problem. A number of experimental and theoretical investigations to develop and substantiate the requirements to sidestick-controlled aircraft handling qualities have been carried out at TsAGI.
The experiments were conducted on TsAGI’s flight simulator PSPK-102 (fig.5) equipped with two electrically loaded sidesticks. Systematical experimental data were received on the effect of sidestick feel system characteristics on aircraft handling qualities for different dynamic performance, flight modes, control axes, etc. Four test pilots tool part in the experiments. Pilot ratings were used [12] to assess aircraft handling qualities.
The experiments showed optimum and Level 1 permissible values of control sensitivity in roll δ_p and pitch δ_{nz}. Fig.6 shows the experimental data on pilot ratings *PR* as a function of control sensitivity in roll for various force gradients. It can be seen that each force gradient corresponds to optimum range of values δ_p corresponding to the highest pilot ratings. When δ_p deviate from the optimum values, pilot ratings worsen. Besides, there is a certain range of force gradients

corresponding to the highest pilot ratings. Force gradient deviation from the optimum leads to pilot ratings worsening. Similar data have been received for the pitch control.
The experimental data on control sensitivity and force gradient effect on HQ are presented in Fig.7 as areas corresponding to Level 1 pilot ratings. In fig.7 the experimental data are shown in circles. It is seen that for large values of force gradient, F_{nz} and F_p are almost constant; for small values of force gradient δ_{nz} and δ_p are almost constant. Thus, we can conclude that forces of an inceptor are decisive for large gradients and displacements are decisive for small gradients.
These data allowed us to develop a method to calculate optimum control sensitivity and feel system characteristics taking into account the control axis, aircraft dynamic and flight mode. The optimum control sensitivity curves based on the method are shown in fig.7. The calculations are in good agreement with experimental data.

3. Pilots' interaction while sidestick control

At the moment, all aircraft with sidestick have "passive" sticks without mechanical linkage, and their interaction is controlled by special algorithm [13,14], which allows two mandatory requirements to be met:

- The ability for each pilot to control the aircraft;
- The ability to neutralize the other pilot incorrect inputs.

For each of the pilots to control the aircraft the integral input signal is the sum of the signals from each sidestick:

$$X_\Sigma(X_1, X_2)=X_1+X_2.$$

In this case the integral signal X_Σ is directly connected with the signal from any control stick $X_\Sigma\ (X_1)$ only if the second stick is in the neutral position, i.e. when X_2=0, $X_\Sigma=X_1$. When the second pilot interferes in the other pilot activity ($X_2\neq0$), the integral signal changes accordingly. For example, if both pilots deflect the sticks simultaneously in the same direction ($X_1=X_2$), the integral signal $X_\Sigma\ (X_1, X_2)$ is equal to

$$X_\Sigma=2X_1=2X_2,$$

This means that the perceived gain from the sidesticks to control surface is twice as much as in the case of single-pilot control. If the pilots deflect the sticks in the opposite directions ($X_1=-X_2$), the integral signal is zero.
Thus, if the other pilot interferes in the control, the aircraft response changes and the first pilot can interpret this interference as a disturbance input. That is why the two pilots simultaneous control is not allowed for the aircraft with "passive" sidesticks.
As in real flight there may arise a necessity to immediately interfere into the control. For these cases, each pilot can take the control "priority" by pushing the "autopilot" knob mounted at a sidestick, which switches off the control signal from the other sidestick.
The development of the so-called "active" sidesticks reproducing mechanical linkage made it possible to compare the assessments of the two types of linkage, which could be based on both pilots' opinions and the experimental data for various flight modes.
The experiments to compare pilots' interaction for "active" (mechanical) and "passive" (algorithmic) sidestick control were conducted on TsAGI's flight simulator PSPK-102; test pilot took part in the experiments. Two types of piloting tasks were considered:

- Concordant control, with the two pilots cooperating
- Discordant control, with one of the pilot interfering in the piloting activity of the other and starting to perform a different piloting task

Assessment of concordant control

Pilots' interaction while concordant control was considered for two piloting tasks, namely:

- Roll tracking, with roll angle varying randomly;
- Straight landing approach, altitude 300 m, distance 7 km, good visibility

Both tasks were performed with both active and passive sidesticks, first for single piloting, then for simultaneous piloting by two pilots.
Both pilots' opinions and piloting accuracy (spectra of tracking errors and stick deflections) were assessed.
The identification of the pilot describing functions was based on the general method [10], but the fact was taken into account that two pilots are in the control. The procedure of the identification process is shown in fig.8. In accordance with the block-diagrams, we can identify closed-loop pilot-aircraft describing function $W_{л\text{-}c}(j\omega)$ as well as the total model

of the two pilots $W_{л\Sigma}(j\omega)$ simultaneously controlling the aircraft (fig.8a) and the models $W_{л1}(j\omega)$, $W_{л2}(j\omega)$ of each pilot separately (fig.8b).
To identify the mentioned describing function the following flight parameters were registered: sidesticks deflections x_1 and x_2, their total deflections x_Σ, bank angle γ and the input signal i.
The random input signal … (the given bank angle) was modeled as a sum of 12 sinusoids:

$$i(t) = \sum_{k=1}^{12} A_k \sin(\omega_k t)$$

The duration of each run was 210 s, the first 10 s were excluded from the processing.
The experimental results for the coordinated control tasks are presented in fig.9. It is amplitudes of frequency responses of the closed-loop pilot-aircraft system for the “algorithmic” type of pilots’ interaction (passive sidesticks) and “mechanical” type of pilots’ interaction (active sidesticks).
The data show that for the passive sidesticks, the amplitude of the frequency responses has a noticeable peaking at frequency ω≈3.5 rad/s, which is due to oscillatory character of the piloting process. For the active sidesticks (mechanical type of the interaction), the resonant peak is lower and correspond to the case of the single-pilot control. The high peaking for the case of passive sidesticks is due to the double gain caused by the summing inputs while two pilots are cooperating and performing the same task.
For the case of active sidesticks, the sticks movement is synchronized, and the total signal is not the sum of the two from each sidestick. As a result, the control signal is similar to the control signal for the case of single-pilot control. This accounted for by the fact that each of the pilots perceives the other’s input immediately and does not take it for a disturbance trying to compensate it. Nevertheless, according to the pilots’ opinions, concordant control of mechanically linked sticks is awkward while performing roll tracking, due to the difference in the manners of piloting and pilots’ correcting each other, which was tiring for both pilots.
In the case of landing approach task, which is not so “agile” comparing with the tracking task, the corrections are of assistance and do not lead to discomfort. It should be added that in the instructor- student case, the perception of the instructor’s piloting by a student pilot is essential for the student to acquire the correct piloting skills.

Assessment of discordant control

Discordant control was assessed for the case when one pilot performs straight landing approach (altitude 300 m, distance 7 km, good visibility) while the other starts a go-around maneuver at the altitude 120 m.
The condition was the pilots’ inability to communicate during the run. Each experimental run was assessed as to the accuracy and the specifics of control. The assessment was given by the co-pilot who was to counteract the input of other pilot, whose response time was also registered.
The experimental results for discordant control are presented in Fig.10, for go-around with passive sidesticks (algorithmic interaction) and with active sidesticks (mechanical interaction).
Two parameters were registered, namely, the moment the co-pilot took control and the moment the other pilot recognized that.

The moment the co-pilot took control was defined as:

- The moment the co-pilot pushed the “priority” knob (for passive sidesticks)
- The moment the co-pilot applied the control force comparable with that applied by the other pilot (for active sidesticks).

The moment the other pilot recognized the co-pilot’s taking control was defined as:

- The moment he returned the stick to the neutral position (for passive sidesticks without linkage)
- The moment he stopped applying any force to the stick (for active linked sidesticks)

Fig.10 shows that in both cases the co-pilot’s taking control was equally quick and reliable. In the case of passive sidesticks without linkage the first pilot had some difficulty in recognizing of the co-pilot’s interference in time (Fig.10a), trying to counteract it for 10 sec.
In the case of active sidesticks (Fig.10b), the co-pilot’s interference was recognized in a few seconds. This means the perception of noticeable change in inceptor forces informs the pilot of the co-pilot interference and of change in the situation and flight mode.
The active sidestick allows some other control system characteristics to be improved. In particular, additional inceptor forces make the performance of critical flight mode limiter more efficient. First, the pilot is warned of approaching a

critical flight mode by the stick vibration, second, the active mode prevention is possible, since stick deflections can be limited or diminished while approaching a critical flight mode. Experiments have shown that active limitation functions are more informative and efficient than the algorithmic limiters currently implemented on aircraft with passive sidesticks. The active sidestick makes the feel system adjustable to the flight mode and piloting tasks, which is especially favorable for piloting accuracy in some cases, much less PIO tendency is an example [5].

Active sidestick deflections can be made simultaneous with autopilot control deflections, thus giving the pilot information on the state of controls, which is most favorably assessed by pilots.

Thus the active sidestick has obvious advantages over the passive sidestick from the point of view of flight safety:

- Pilots' direct tactile interaction while co-piloting while training student pilots or for assisting the counterpart or in a critical situation in flight
- Adjustability of feel system characteristics to flight modes and piloting tasks
- Demonstrable and easily perceived limiter performance
- Automatic control system operation monitoring

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Figures

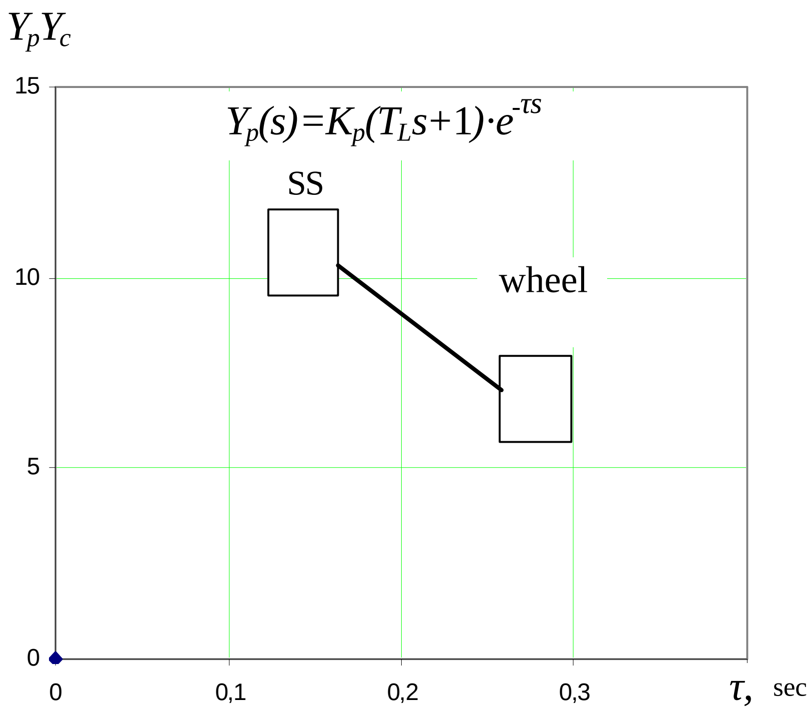

Figure 1: The effect of types of inceptor on pilot aircraft open-loop system gain and pure time delay

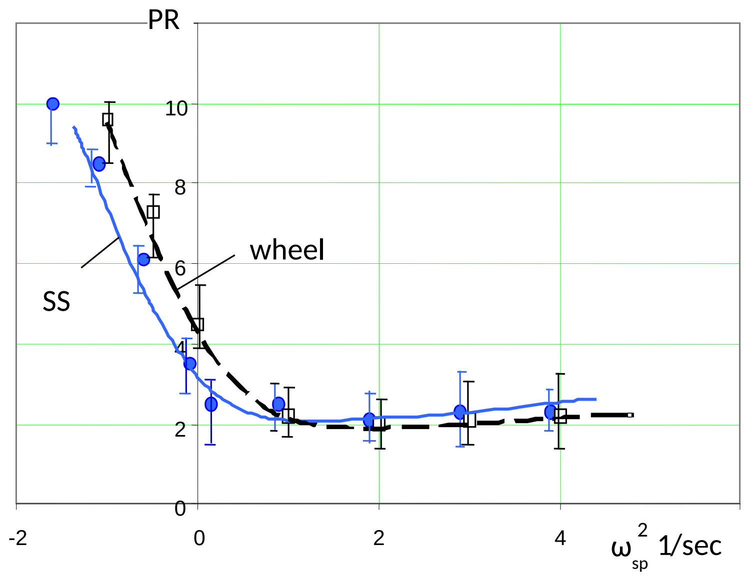

Figure 2: Pilot rating vs short period frequencies squared

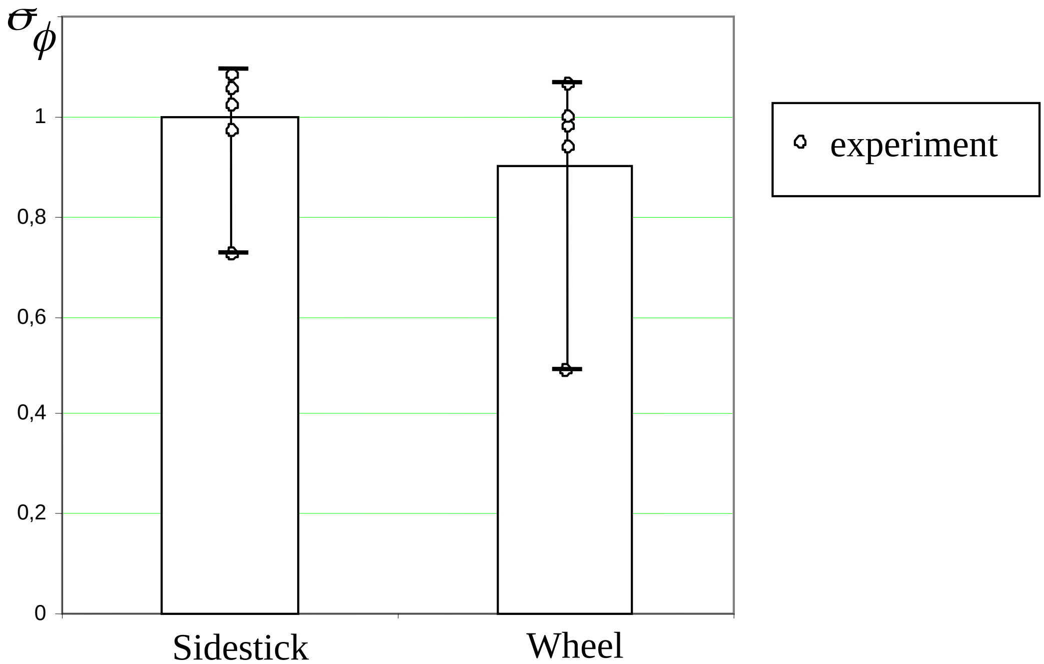

Figure 3: Roll tracking accuracy for a sidestick and wheel

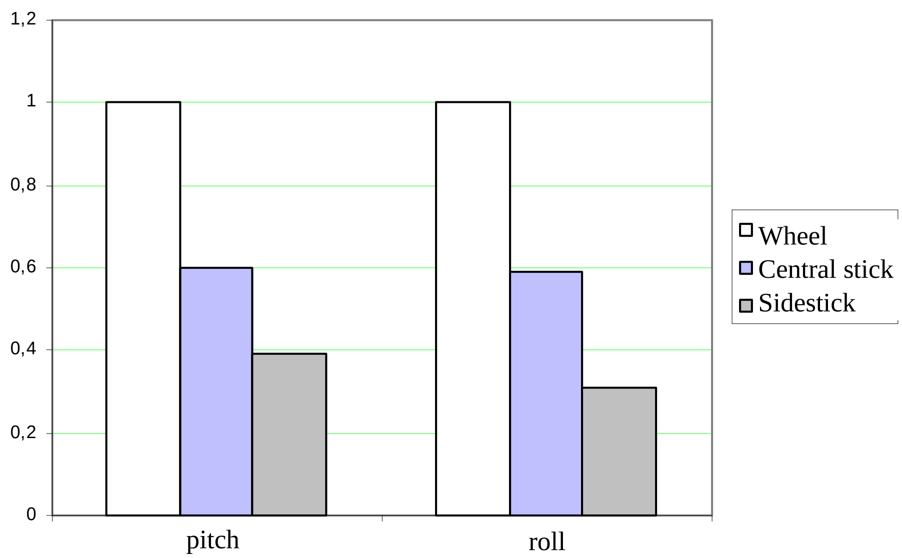

Figure 4: Shaping accuracy for different inceptors

Figure 5: Flight simulator FS-102 TsAGI

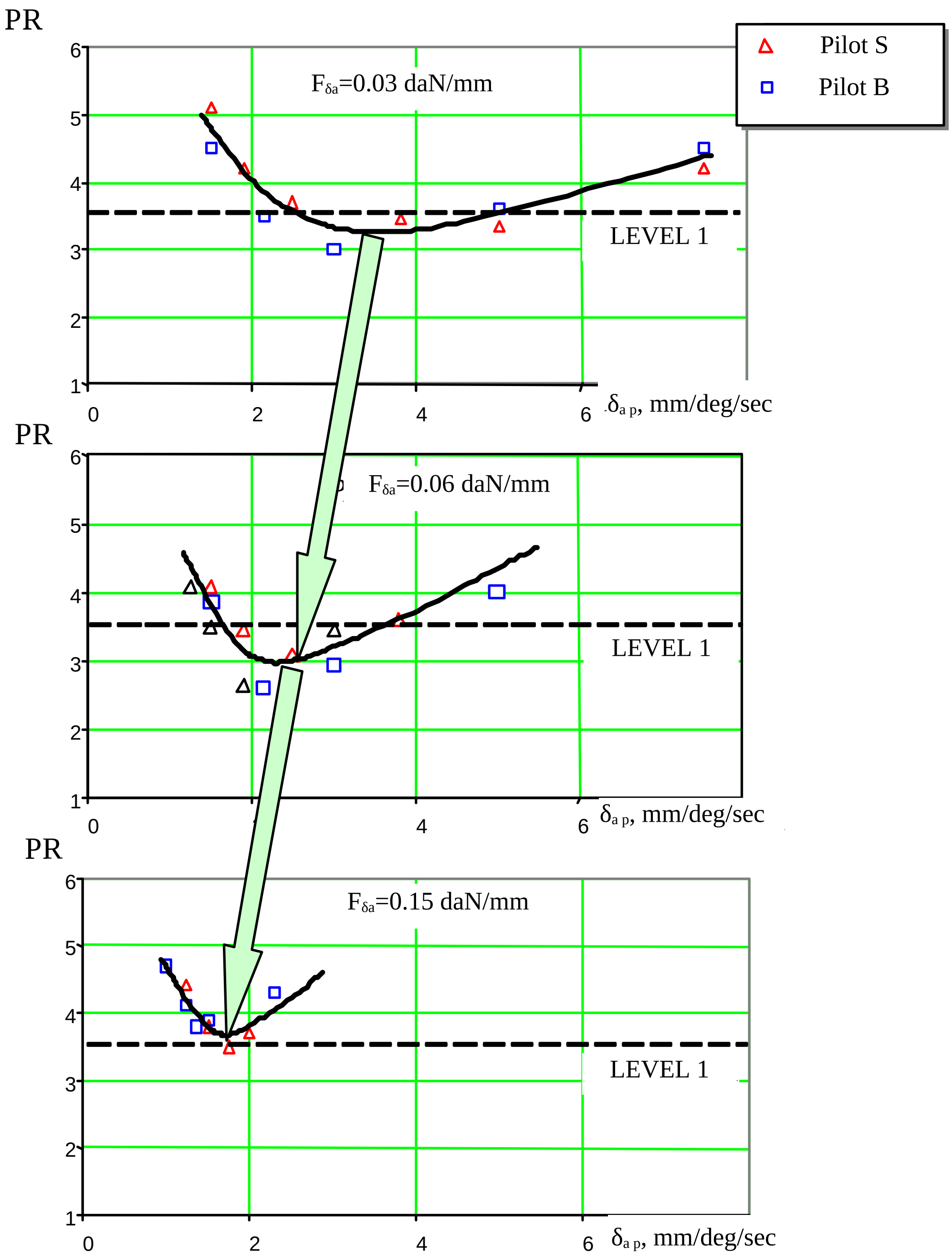

Figure 6: Effect of control sensitivity and force displacement gradient on pilot ratings

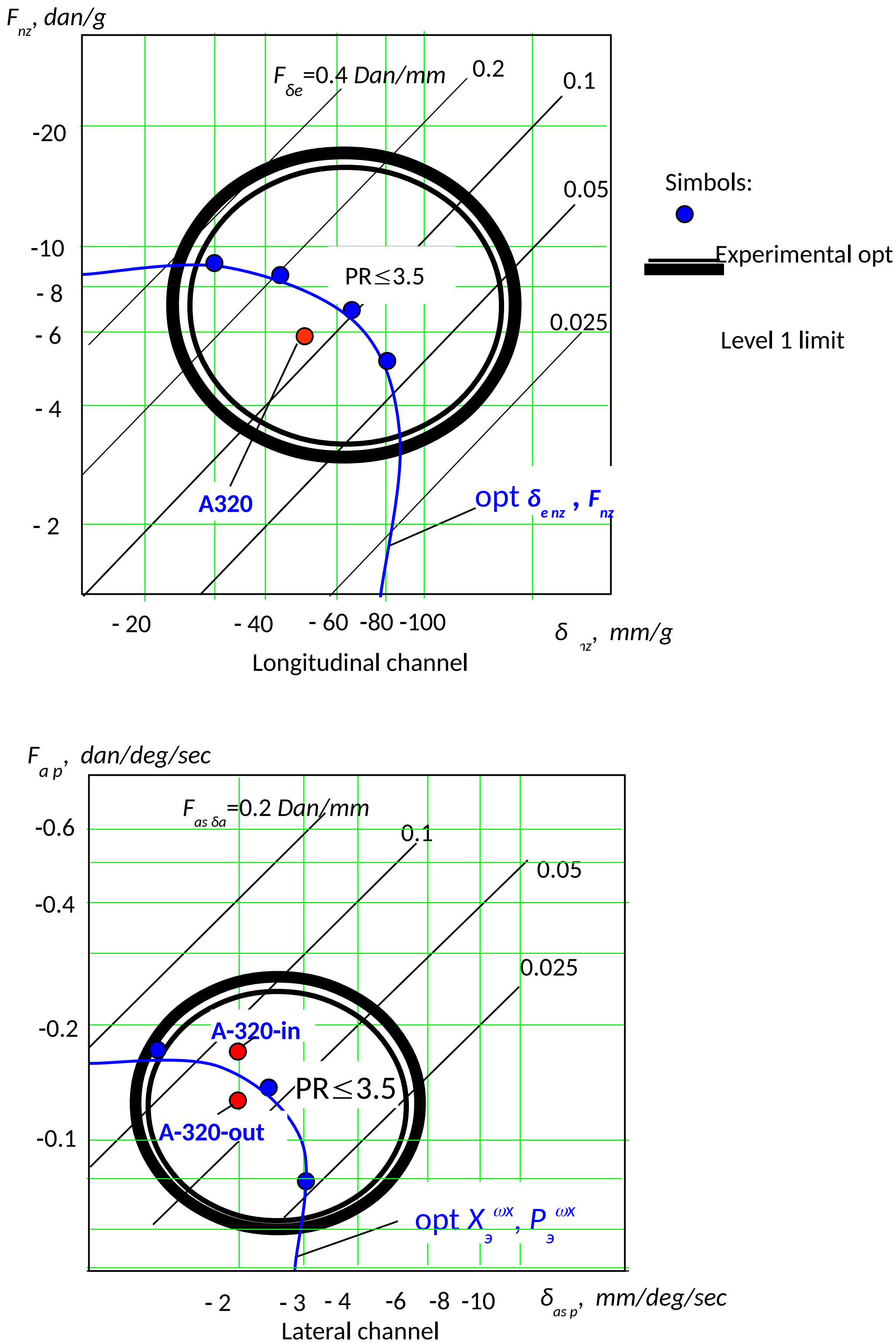

Figure 7: Areas of optimum control sensitivity and force gradients in pitch and roll

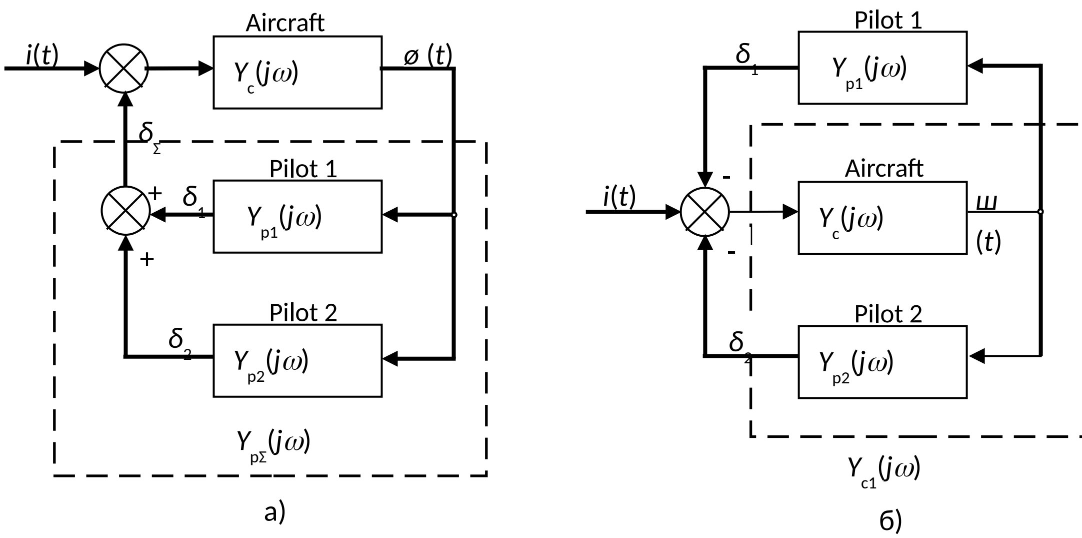

Figure 8: Block diagrams to identify describing functions for two-pilot control and single-pilot control

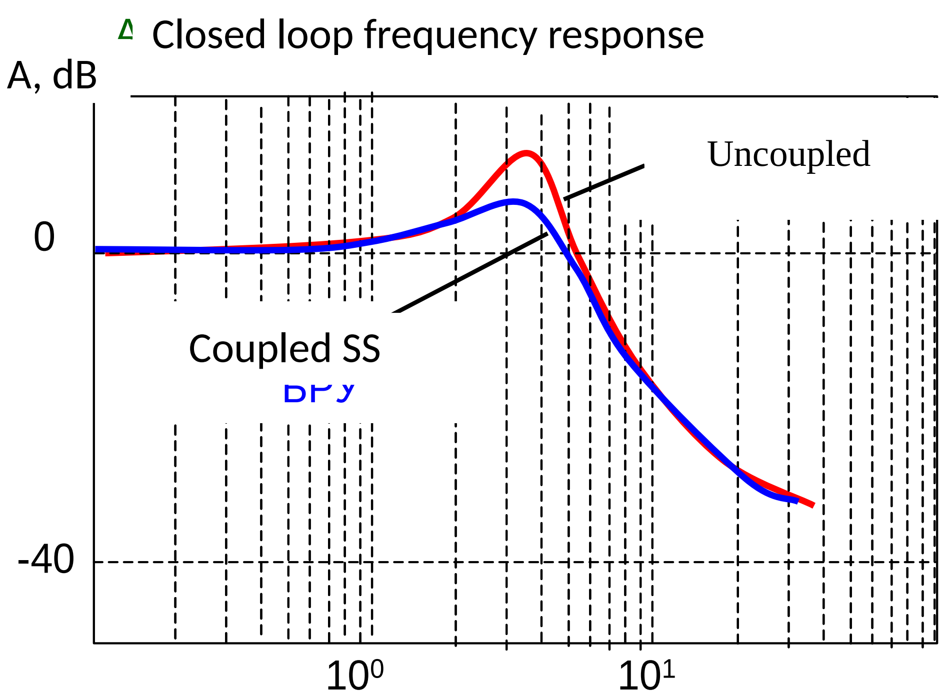

Figure 9: Closed-loop freqency response for copled and uncoupled control

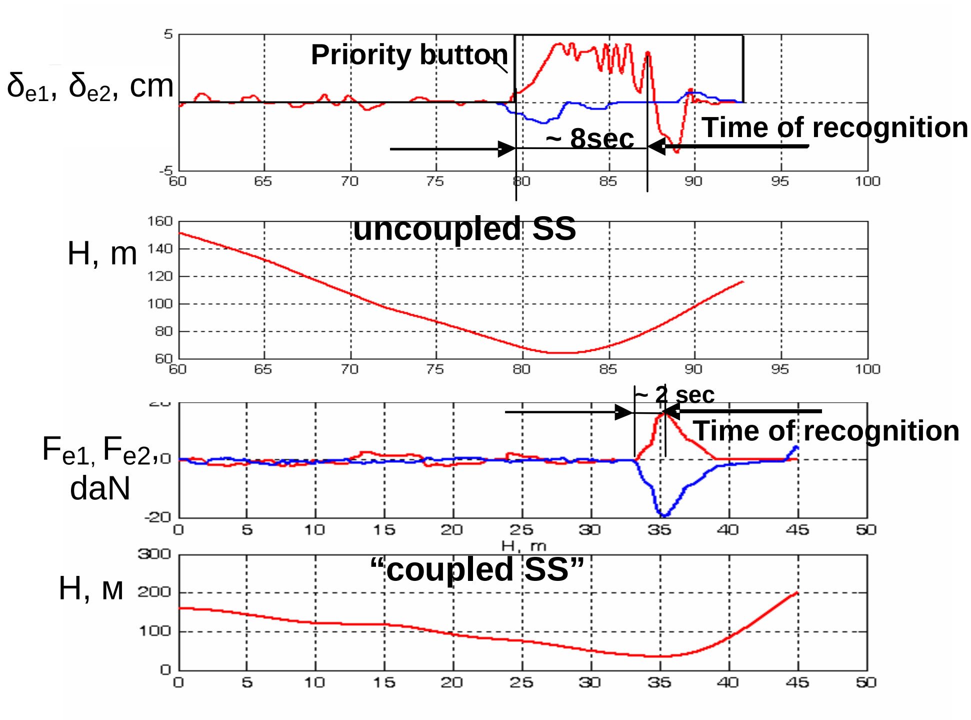

Figure 10: Time histories for uncoupled and coupled control