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Investigation of Manual Control Behaviour during Flight Control Mode Switching: Test Procedure and Preliminary Results

Andrej Schönfeld

Abstract This paper describes pilot-in-the-loop experiments that are used to investigate peculiarities in manual control behaviour in case of flight control law reconfiguration. In such situations a closed-loop pilot-vehicle system (PVS) instability can occur that manifests itself in the form of an unwanted oscillatory aircraft reaction called “pilot-involved oscillation” (PIO). A focus of the experiments was to provide an answer to the question, whether PIOs can occur following sudden flight control mode switching, even if the aircraft dynamics before and after switching are not rated PIO-prone. The determination of linearised aircraft dynamics from a nonlinear aircraft model is described and a handling qualities database is presented. Linearised aircraft have been determined for the aircraft with augmentation by flight control laws and with direct link between pilot inceptor and control surface. An explanation of the test station, the flying task and the conduct of the experiments is given. Preliminary results are shown and conclusions regarding the experimental approach are drawn.

Symbols

A_k	k-th amplitude of input signal
K_D	display gain coefficient
M_q	dimensional derivative of pitch damping
T	duration of simulator trial
T_0	fundamental period
Y_FS	transfer function of force feel system
$Y_\mathrm{W}(s)$	transfer function of form filter
$e(t)$	error signal observed by the pilot

Andrej Schönfeld, Research Scientist
TU Berlin, Marchstr. 12, 10587 Berlin, e-mail: andrej.schoenfeld@gmx.de

$i(t)$	input signal
l_μ	aerodynamic mean chord
s	Laplace variable
t	time
t_{SW}	switching time
$t_{\rho,\max}$	time lag between stick deflection and pitch rate
$\Theta(t)$	current pitch attitude
$\Theta_{\mathrm{C}}(t)$	commanded pitch attitude
ζ_{A}	damping coefficient of actuator
σ	standard deviation of input signal
φ_{k}	k-th phase angle of input signal
$\Delta\varphi$	phase lag between stick deflection and pitch rate
ω_0	fundamental frequency
$\omega_{0\mathrm{A}}$	natural frequency of actuator
ω_{i}	corner frequency of input signal
ω_{k}	k-th input frequency
ω_{osc}	oscillation frequency

1 Introduction

Modern commercial transport aircraft are equipped with digital full authority fly-by-wire flight control systems. This permits the design of task-tailored flight control modes and allows to reconfigure the flight control system in case of system failures.

A manual multi-mode flight control system must be designed considering closed-loop pilot-vehicle system (PVS) behaviour. Transitions between modes must be carefully investigated in flight tests to assure that no unwanted aircraft reaction follows these transitions. This might even happen, if both flight control modes are properly designed. Reason for that is the minimum amount of time a human pilot needs to adapt to the new effective aircraft dynamics. An excellent summary on adaptive human pilot behavior was written by Young [20].

An undesired handling qualities phenomen that can occur in such a situation, is a “pilot-involved oscillation” (PIO) [5]. This is a closed-loop phenomenon of the PVS, where the pilot drives the aircraft unintentionally into oscillations while he exerts tight control or initiates abrupt maneuvers. In both cases an improper design of the augmented aircraft dynamics is regarded to be the reason for that. For the emergence of a PIO a trigger event is necessary. Mode switching involves at least two different sets of effective PVS dynamics: pre- and post-transition.

Many investigations in the past have been directed to the causes and to the prediction of PIOs. In the mid of the 1990s [5] a systematic PIO classification has been adopted, which classifies the PIO occurences due to their contributing factors into three categories: Category 1 (only linear effects), Category 2 (due to rate or postion limits) and Category 3 (all other nonlinear effects). Control mode switching belongs to Category 3. To the knowledge of the author, no systematic experimental investigation of Category 3 PIOs has been conducted yet, whereas Category 1 or 2 PIOs have been investigated in several studies (e.g. [2], [15], [7] and [3]). This paper offers a method for investigation of PIOs following sudden flight control mode switching.

First of all, a handling qualities database, consisting of state-space models, has been generated that allows investigating transitions from augmented aircraft dynamics to unaugmented aircraft dynamics. Those aircraft dynamics have been derived from a nonlinear aircraft model. Next, an experimental set up has been designed to investigate PIO susceptibility in case of flight control law reconfiguration. Special attention has been paid to the choice of the flying task, the rating scales and the permutation of simulator trials. Ten pilots participated in the experiments that were conducted using a fixed-based research test station. At the end of the paper the success in exciting PIOs is shown and conclusions regarding the experimental approach are drawn.

2 Determination of Handling Qualities Database

In this study flight control law reconfiguration was supposed to occur from augmented to unaugmented aircraft dynamics. In the following those dynamics will be refered to as normal and direct law, respectively. Because the switching usually occurs in failure conditions, it results in a degradation of the aircraft dynamics. Low manual flying experience of an airline pilot in direct law may aggravate this situation, since the pilot has to adapt to an unknown aircraft dynamics.

Different aircraft dynamics in normal and direct law were defined for the experiments. They were obtained from a low order equivalent systems identification [4] of a nonlinear aircraft model. This model consists of the flight test identified aerodynamics, actuator dynamics, sensors and flight control laws of the VFW-614ATD. The aircraft was a technology demonstrator of the Airbus Deutschland GmbH that was developed for basic research in fly-by-wire technology. A peculiarity of the aircraft is the positon of the engines on top of the wings. The flight control system consists of normal law (load factor demand in longitudinal axis) and direct law.

For identification of the aircraft dynamics the reference states have to be defined. Scenario A is a horizontal flight segment in 3000 ft with flaps in CONF 2, gear retracted and speed of 170 kts (TAS). Scenario B is a power approach beginning in 3000 ft with a path angle of $-3\,$deg, CONF 3, gear extended and a speed of 150 kts (TAS). In every scenario four different centre of gravity positions have been chosen, making up a total of 16 identified aircraft dynamics (8 in normal law, 8 in direct law). Every reference point was labelled as shown in Table 2.

Aircraft dynamics were identified as state space models [19]. The identified equivalent time delays turned out to be very high (180 - 220 ms) compared to MIL-STD-1797A [18] requirements due to the actuators and the platform design. Since it was considered that a production aircraft would have optimized flight control system components, a general reduction in time delay of 80 ms seemed realistic. Moreover, the command gain of the aircraft dynamics was generally increased by a factor of two, because the sidestick used for the experiments has only limited deflection range

centre of gravity	16% l_μ	21% l_μ	26% l_μ	32% l_μ
scenario A	1	2	3	4
scenario B	5	6	7	8

Table 2 Labels of reference points

compared to an Airbus sidestick. The actuator has been modelled as a second order transfer function with a damping coefficient of $\zeta_{\mathrm{A}} = 0.7$ and a natural frequency of $\omega_{0\mathrm{A}} = 45$ rad/s. The equivalent time delay of the actuator dynamics has been subtracted from the time delay.

To increase the number of aircraft dynamics in the database the direct law dynamics were systematically modifed. The parameters time delay, control sensitivity and pitch damping were varied. For the simulator campaign the mode switching was always constrained to the scenario of the normal law. No switching between the scenarios occured. The number of possible switchings was limited to 32, the number of normal law dynamics to four.

The final selection of the aircraft dynamics was effected by 1) the difference in amplitude gain between normal and direct law and 2) the difference in the criterion values of the Neal-Smith-Criterion. The selected switching constellations are given in Table 2 [1] The labelling of the constellations complies with the labelling of the aircraft dynamics. Only one aircraft dynamics occurs two times in the table (6-A1 and 7-A1 are the same aircraft dynamics). The state-space models of the dynamics can be provided by the author.

3 Apparatus

3.1 Simulation Hardware

A fixed-base handling qualities research station, shown in Fig. 1, was used for this investigation. It consists of an active sidestick[2], a pilot seat, two monitors and three computers.

The sidestick is equipped with an armrest and mounted on the floor. It is adjustable in height and attitude (roll and pitch). Force and deflection signals of the sidestick are sent to the interface computer via the control box and the patch panel.

The pilot seat is mounted on tracks to enable movements back and forth. This allows the pilot adjusting his position relative to the stick before conducting the experiments.

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[1] The first number represents the normal law dynamics and the letter the centre of gravity position.

[2] Stiffness and damping of this sidestick can be varied.

Direct Law				Scenario A		Scenario B	
				NL 2 CG = 21%	NL 4 CG = 32%	NL 6 CG = 21%	NL 7 CG = 26%
CG[I]	G[II]	$\Delta\tau$[III]	k_{M_q}[IV]				
16%	1	0	1		4-A1	6-A1	7-A1
16%	1	0	0.75				7-A2
21%	1	0	1	2-B1		6-B1	
21%	1	0	0.75		4-B2		
26%	1	0	1				7-C1
26%	1	0	0.75			6-C2	
32%	1	0	1		4-D1	6-D1	
32%	1	0	0.75	2-D2			
n.c.	0.5	40	0.75	2-E1	4-E1	6-E1	
n.c.	0.75	40	1	2-E2			
n.c.	1	80	0.75	2-E3	4-E3		7-E3
n.c.	1.5	0	0.75	2-E4	4-E4		7-E4
n.c.	1.5	40	1			6-E5	
n.c.	2	0	1	2-E6	4-E6	6-E6	7-E6
n.c.	2	40	1				7-E7
n.c.	3	80	0.75	2-E8	4-E8	6-E8	7-E8

[I] CG = centre of gravity: indicated in percentage of aerodynamic mean chord l_μ. The entry "n.c." (not changed) indicates the same CG as for normal law.

[II] G = gain: influences the control sensitivity of direct law dynamics. A value of 1 indicates no change to the original gain of the direct law dynamics.

[III] $\Delta\tau$ = change in time delay: indicated in ms. A positive value represents an increase in equivalent time delay of the direct law dynamics.

[IV] k_{M_q} = scale factor of the dimensional derivative M_q of the direct law dynamics. A factor k_{M_q} lower 1 means a reduction in the dimensional derivative.

Table 3 Listing of all aircraft dynamics and switching constellations

All computers are Windows XP® PCs that are interconnected by Ethernet. On the right monitor, which is connected to the display computer, the display is presented to the pilot. The left monitor is connected to both other computers and serves as the interface to the flight test engineer for simulation control.

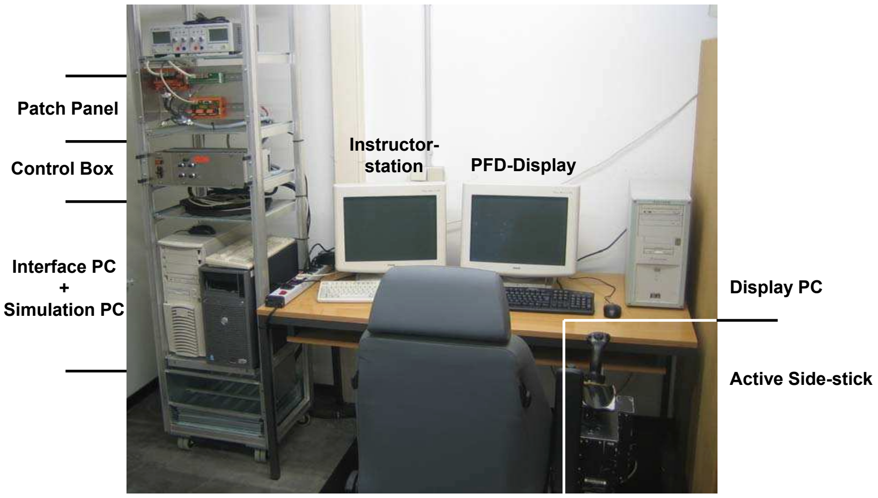

Fig. 1 Handling qualities research station of TU Berlin's Department of Flight Mechanics, Flight Control and Aeroelasticity

3.2 Simulation Software

The flight simulation software is split into three modules: a simulation module, an interface module and a display module. Each module runs on a separate computer for performance reasons. They communicate via UDP.

The interface module receives the measured stick force and stick deflection signals at a rate of 200 Hz. Those analogue signals are converted to digital values with a 16-bit A/D-converter card and are sent to the simulation module. At the same time the interface module receives the desired values for stiffness and damping from the simulation module and sends them to the control box. There the control algorithm of the sidestick is implemented.

The simulation module queries the control inputs from the interface module and simulates the aircraft dynamics in real-time. The output signals are calculated every 10 ms and are kept in memory until the end of the simulation run. Then the values are saved to the hard disk. A subset of signals is sent to the display module every simulation step.

The flying task was implemented using a specially prepared SIMULINK® model. A startup callback function calculates the input signal and loads the requested aircraft dynamics into workspace. The request is done in an external text file. Finally, the Real-Time Workshop® Embedded Coder™ translates the SIMULINK® model into an executable file with real-time behaviour. After every simulation run a counter is increased that is saved in a separate text file. By changing the counter manually an arbitrary test setup can be selected.

The display module continuously updates the display. If no new values have been received, the last set of values will be displayed. The current frame rate was shown on the display. During all experiments it was higher than 100 Hz.

3.3 Display

A primary flight display (PFD), see part of the display in Fig. 2, shows all information that is required to perform the flying task to the pilot. For all experiments the speed value, the altitude and vertical speed were set to fixed values (170 kts, 3000 ft, 0 ft/min). This was done, because pilots shall detect a switching only by the difference in aircraft control behaviour. Therefore, only current aircraft attitude $\Theta(t)$ and current command signal $\Theta_C(t)$ are displayed to the pilot. The command signal is displayed by the horizontal flight director bar.

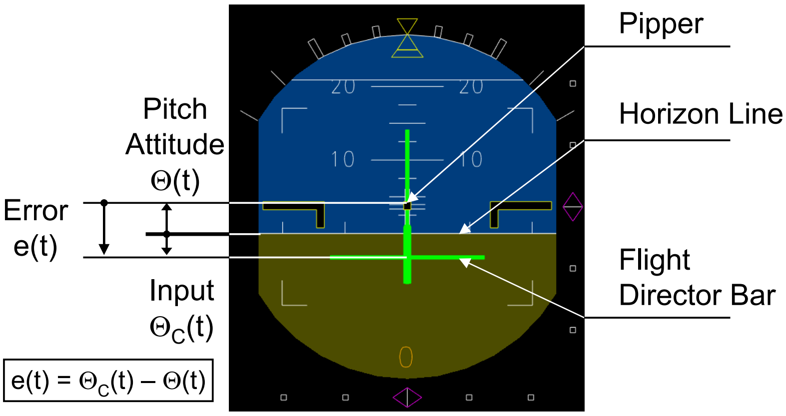

Fig. 2 PFD used for the experiments

3.4 Sidestick Characteristics

Values for stiffness and damping were selected for the experiments that were held constant for all runs. The force-deflection curve has been determined experimentally (s. Fig. 3). The characteristics have been estimated by the bold lines and are given in Table 3.4[3]. Backlash has not been identified.

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[3] The deflections have been determined during the simulator campaign. To conduct the experiments the output voltages have been scaled to estimated deflection values. Those turned out to be lower by a factor of approximately 0.885 (0.89 in push and 0.88 in pull) compared to the actual values.

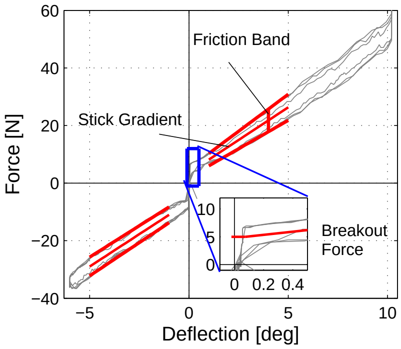

Fig. 3 Deflection-force curve of sidestick

Stiffness [N/deg]	4.5[a]
Min. Defl. [deg]	-6.0
Max. Defl. [deg]	10.2
Breakout Force [N]	5.0 (Pull) 7.0 (Push)
Friction [N]	
	1.54 + 0.6 × Defl. (Pull)
	2.62 + 0.13 × Defl. (Push)

Table 4 Stick Force Characteristics

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[a] This is the medium value of push and pull direction. The maximum deviation from the given value is 0.046 N/deg.

Dynamic stick behaviour has also been identified experimentally. The describing function in (1) has been obtained in pilot tests by choosing a polyharmonic input signal with input frequencies between 0.264 and 36.6 rad/s

$$Y_{\mathrm{FS}} = \frac{170.0}{s^2 + 2\cdot 0.78\cdot 30.6\,s + 30.6^2} \qquad [\mathrm{deg/N}]. \tag{1}$$

It is important to note that the stick deflections noticeably influenced the tracking task. The asymmetric deflection range limited the maximum control authority in the push direction. This was commented on by most pilots. Stiffness and breakout forces were rated as high, but still ok by all pilots. Some pilots noted the backlash in the stick, but most pilots did not feel uncomfortable with it.

4 Experimental Design

4.1 *Flying Task*

The task to be flown by the pilot was a single-axis pursuit tracking task. The block diagram of the closed-loop pilot-vehicle system is shown in Fig. 4. Both commanded pitch attitude $\Theta_C(t)$ and actual pitch attitude $\Theta(t)$ are shown on the display (s. Fig. 2). The pilot has to aggressively reduce the tracking error $e(t)$ by sidestick deflections. Those are used as the command input for the aircraft dynamics. At a specified time t_{sw} the dynamics switch from the normal law dynamics to the direct law dynamics and the pilot has to adapt to the new situation while continuing the tracking task. In a real aircraft the aircraft reaction is detected by sensors. For the experiments the sensor dynamics have been neglected, resulting in a measurement transfer function of 1.0.

This closed-loop PVS is valid for all test runs (trial). Each trial lasts for $T = 144$ sec. If the switching time is set to $t_{\mathrm{sw}} = 0\,\mathrm{sec}$, the pilot flies only the direct law

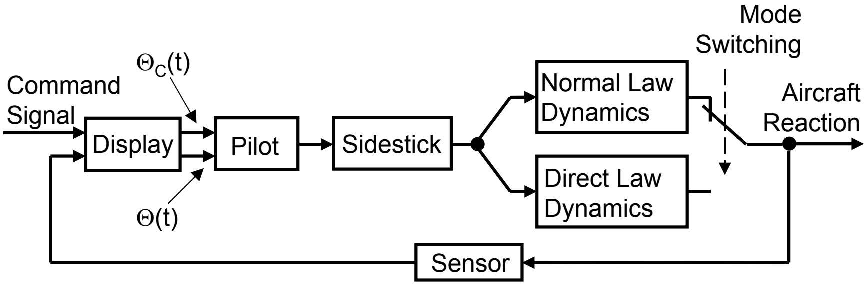

Fig. 4 Closed-loop pilot-vehicle system during flying task

dynamics. On the contrary, the pilot flies only the normal law dynamics, if $t_{\mathrm{sw}} >= T$. For every switching time in between a switching in the aircraft dynamics occurs, where the pilot has to adapt his control behaviour. In the experiments the switching always happened at $t_{\mathrm{sw}} = 48$ sec. The pilots did not know whether or when a mode switching occurs.

The pilots were told to minimize the error as aggressively as if they would perform a CAT I approach with strong turbulence. For the use of the rating scales desired and adequate performance limits were defined. For desired performance the tracking error should be within ±1 deg and without any tendency of PIO. Adequate performance is achieved within ±2 deg.

4.2 Input Signal

The command signal $i(t)$ is polyharmonic in nature and consists of 15 harmonics with amplitudes A_{k} that are almost equally spaced in logarithmic scale.

$$i(t) = \sum_{k=1}^{15} A_{\mathrm{k}} \sin(\omega_{\mathrm{k}} t + \varphi_{\mathrm{k}})\,. \tag{2}$$

All parameters of the input signal are given in Table 5. Its frequencies ω_{k} are integer multiples of a fundamental frequency ω_0. This frequency is determined by:

$$\omega_0 = 2\pi/T_0, \tag{3}$$

with the fundamental period $T_0 = 24$ sec of the input signal. By repeating the input signal every 24 sec the overall input signal is generated. The standard deviation of the input signal equals $\sigma = 2\,\mathrm{deg}$.

The amplitudes A_{k} were calculated according to the approach described in [8]. The input signal resembles a Gaussian white noise signal filtered by a second order form filter $Y_{\mathrm{W}}(s)$

k	ω_k [rad/sec]	A_k [-]	φ_k [deg]	k	ω_k [rad/s]	A_k [-]	φ_k [deg]
1	0.2618	2.3	180	9	3.1416	0.023	180
2	0.5236	1.48	0	10	3.927	0.013	180
3	0.7854	0.605	0	11	5.236	0.006	0
4	1.0472	0.296	0	12	6.2832	0.0042	0
5	1.309	0.188	180	13	7.854	0.0027	180
6	1.5708	0.127	180	14	10.472	0.0015	180
7	2.0944	0.058	0	15	15.708	0.00095	0
8	2.618	0.034	0				

Table 5 Parameters of the input signal

$$Y_W(s) = \frac{1}{(s+\omega_i)^2} \qquad \text{with } \omega_i = 0.4\,\text{rad/sec}\,. \tag{4}$$

This kind of input signal was preferred for the investigation for two reasons. First, the sum-of-sines tracking is regarded as appropriate to excite Category 1 PIOs [16]. As there is no experience on optimum input signals for Category 3 PIO investigations, the polyharmonic signal was chosen. Second, this signal allows analyzing the experimental data by Fourier or wavelet transforms.

4.3 Display Dynamics

The display was scaled to the monitor dimensions. No time delay or filter dynamics have been added, so the display dynamics can be approximated by a gain coefficient K_D. The value of K_D equals 0.32 at a distance of approximately 60 cm (assumed eye position of the pilot). This is equivalent to a reduction by a factor of three in the pilot perceived error signal. This might induce threshold effects, but it was preferred by the airline pilots because of the similarity to normal aircraft operation.

4.4 Pilot Questionnaire

The pilot had to assign three different ratings: the Cooper-Harper rating (CHR, [6]), the PIO tendency rating (PIOR, [18]) and, in case of control mode switching, a transient failure rating (TFR, based on [9]). The first two rating scales are typically used in handling qualities investigations are explained and discussed e.g. in [10], [12], [13], [1] and [14].

A TFR scale, see Fig. 5, was originally developed at TsAGI ([9]) for evaluating the effects of mode switching or system failures. Compared with the original scale the wording has been modified to make it more consistent with the other rating scales[4]. Similarly, it is based on the penalty principle. After confirmation that a transition is noticeable, all following questions have to be negated to obtain good ratings. A rating of TFR 5 has to be given, if the pilot considers the transition to be dangerous. Otherwise he has to decide, whether the precision of the flying task is affected.

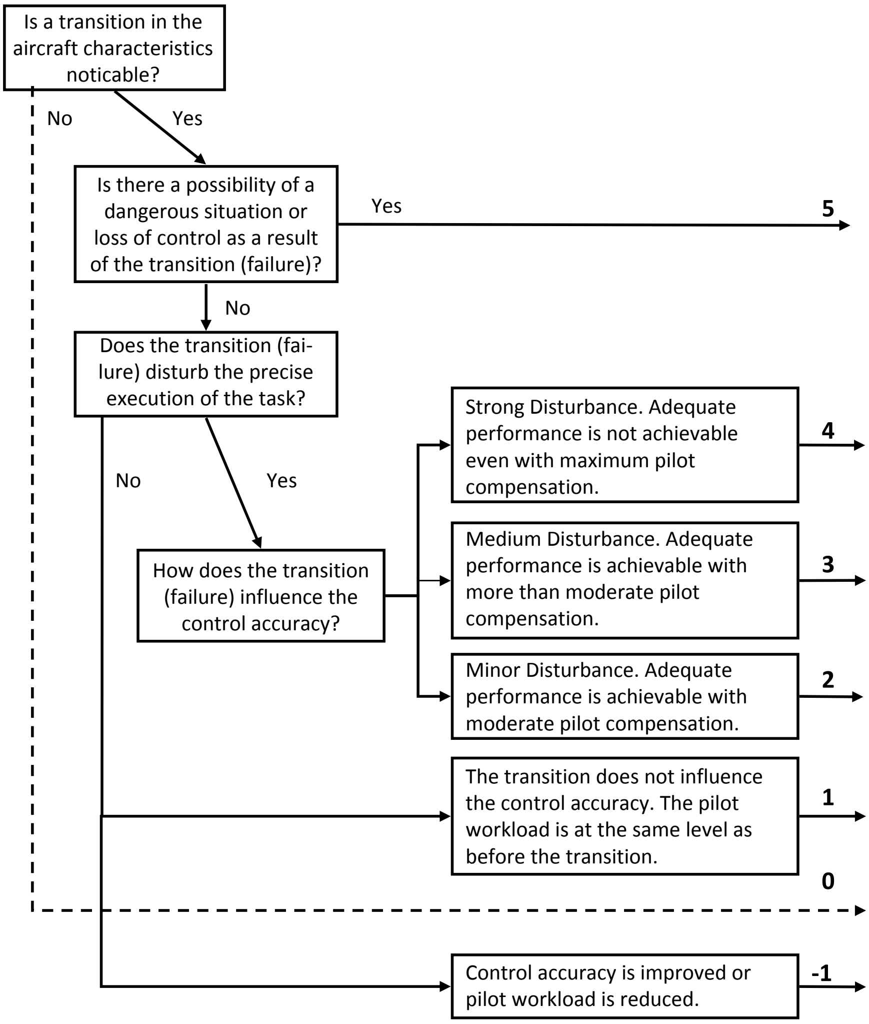

Fig. 5 Transient failure rating scale

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[4] The terms "adequate" and "compensation" have been used in their meaning of the Cooper-Harper Rating Scale.

In case of performance degradation TFRs between 2 and 4 apply. The distinction between the ratings is made only by the required pilot compensation, not by the achieved performance[5]. If adequate performance is achieved with not more than moderate pilot compensation a TFR 2 has to be given. A TFR 3 means that more than moderate pilot compensation is needed to achieve adequate performance. If adequate performance is not attainable at all a TFR 4 must be given.

In case of no performance degradation the pilot also has to decide between two ratings. A TFR 1 indicates no performance change. The rating TFR -1 has to be given, if either the task performance improves or the workload is reduced.

Other rating scales for evaluation of transient effects exist (e.g. [11] and [17]), but the TFR scale was chosen. One reason for the decision was the question, whether a transition in the aircraft dynamics is noticeable. That question allows for the possibility that no switching is noticed, which is important in testing acceptable transitions. The other scales implicitly assume a detected mode switching. Another reason was the simplicity in answering the questions. The pilot has to follow a simple decision tree and gives only one final rating.

Additionally, the pilot had to evaluate initial attitude response (IAR), predictability of final response and pitch sensitivity after each trial. The IAR is a measure of responsiveness. If it is too low, the pilot may feel a sluggish aircraft response. If the reaction is too strong, than the aircraft tends to overcontrol. Predictability is equally important for good ratings. Only if the pilot can predict the final aircraft response from his first deflections, he will be satisfied with the aircraft. Otherwise it may drift away from the desired value or oscillate around it. Both is very difficult to predict for the human pilot. The pitch sensitivity gives information about the ease with which a pilot is able to reach a desired value. If the aircraft reaction to stick deflection is too sensitive, the pilot has difficulties to achieve the desired value. If it is not sensitive enough, the pilot needs large deflections for achieving the desired attitude.

4.5 Test Procedure

A simulator session with one pilot was split into four blocks: a training block, two switching blocks and a direct law block. The order of the blocks was especially chosen to force the pilot to adapt to unknown aircraft dynamics. Because of the limited amount of simulation time, every pilot could fly only two different normal law dynamics. The blocks were preceded by a briefing and superseded by a debriefing.

The objective of the training block was to familiarize the pilot with the flying task, the rating scales and the test station. First, the pilot flew a normal law dynamics repeatedly, as much as he needed to get familiar with the flying task and to develop a certain level of aggressiveness. Next, he flew two trials with different direct law dynamics (every pilot flew the same dynamics) where he had to assign CHR and PIOR. The evaluations were discussed with reference to the ratings of the first test

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[5] For these experiments it was considered that in case of degradation due to mode switching desired performance does not has to be achieved during transition phase.

pilot. The discussion deemed necessary as the airline pilots were not familiar with the rating scales and their difficulties (s. [14]). The reference to the test pilot was made to give a standard for further evaluations.

A switching block began with two trials of the same normal law dynamics (NL) without mode switching. Only after the second trial the pilot rated the aircraft dynamics. The nine following trials began always with the same normal law dynamics. In only one of those trials no switching to direct law dynamics occurred. The order of the trials was permuted for each of the pilots (s. Table 6). Two different permutation patterns have been used, where the order of the direct law dynamics was varied (B - weak transition, C - noticeable transition). Before the trials all configurations have been assigned to either group B or C.

Trial No.	1	2	3	4	5	6	7	8	9	10	11
Pattern A	NL	NL	C	B	C	C	B	C	NL	C	B
Pattern B	NL	NL	B	C	C	NL	C	B	C	C	B

Table 6 Permutation patterns of switching block

In the direct law block no switching occurred, so the pilot was flying a stationary tracking task. He had to fly and to evaluate ten different direct law dynamics that he had flown already before (five from each switching block). To get a minimum number of repetitions, only those aircraft dynamics with the biggest difference in system behaviour were evaluated. The intention of this block was to check, whether a difference in rating can be observed comparing the ratings of the stationary tracking task with the ratings of mode switching.

5 Experiment Execution

5.1 Subjects

The experiments were flown by ten male pilots (2 test pilots and 8 airline pilots), s. Table 7. All pilots had experience on fly-by-wire sidestick controlled transport aircraft. Some of the airline pilots participated in research experiments before.

5.2 Briefing

During the briefing the pilots were introduced to the flying task (including mode switching) and to the use of the rating scales. They were instructed that a mode switching can occur, but does not have to. Since airline pilots never get in touch

Pilot	FH (FbW)	Type Rating	Prev. Ratings	Comments
A	9.000 (1.000)	B 757/767	A300/310, A320, B737, A330/340	aerobatics, glider, flight test engineer (in education)
B	4.400 (2.000)	A320-family, C525	EF2000, Tornado, F-4F, Alpha Jet, Do 228, Canberra	aerobatics, German Air Force, test pilot
C	12.000 (3.500)	A330/340 (ret.)	B747-200	
D	10.000 (8.000)	MD-11	A320-family, A330/340, A340-600	
E	10.000 (10.000)	A320	A330/340, A340-600	flight instructor
F	24.000 (10.000)	A320 (ret.)	A340, A310, B727, DC3, B707, V814	aerobatics, air races, glider
G	11.700 (7.400)	A320/330, B737	C421, C525, F27	aerobatics, glider, flight instructor, type rating instructor
H	1.200 (1.200)	A320-family		
I	1.800 (1.000)	A320/330	CRJ 200/700/900	glider
J	2.000 (400)	A318/319/320/321, Do 228	PA42	test pilot (TB2), glider

Table 7 List of all pilots

with rating scales, special focus was put on the explanation of the Cooper-Harper Scale and the PIO tendency rating scale [10, 14]. The pilots were not explicitly asked to search for PIO tendencies during mode switching.

Pre-tests have shown that the asymmetric stick deflection range disturbs the tracking task during flying in normal law. It turned out that during fast changes of the input signal the pilot was not able to follow the command while reaching deflection limits. To overcome this problem and to keep a certain level of aggressiveness, the pilots were told that the flying task consisted of two alternating phases: acquire and tracking. During the acquire phase the pilot tries to follow a fast changing input signal and may reach the deflection limits, possibly leaving adequate performance limits. As this is related to the experimental setup and not necessarily to aircraft dynamics, these phases shall be disregarded for evaluation of CHR and ratings had to be assigned only for tracking phases.

For trials without switching only CHR and PIOR had to be given. They should be assigned for the overall run, neglecting the first seconds required for adaptation to the new dynamics. In case of mode switching the TFR shall be assigned for the transient phase, until the pilot feels adapted to the new dynamics, and the CHR for the period after the transient phase. The PIOR should be given for the overall trial, where the worst situation is to be rated.

5.3 Trials

After each trial the pilot had to answer the questionnaire. First, he had to assign the ratings, then he had to evaluate the IAR, predictability of final response and pitch sensitivity. For shortening the simulator sessions the pilots were encouraged to comment on the characteristics already during the trials. In case of switching, all comments had to be given for the new aircraft dynamics.

5.4 Debriefing

After all trials the pilots were informed, how many mode switches they did not detect. They were asked about the course of the experiments, whether they noticed some form of learning effect, fatigue, etc. At the end they were asked about their operational experience with PIOs.

6 Evaluation and Preliminary Results

6.1 Evaluation

All trials have been checked for the occurrence of PIO. An algorithm, similar to the ROVER algorithm ([16]), has been applied to the time traces of pitch rate and stick deflection. It estimates the phase lag $\Delta\varphi$ between pilot command and aircraft reaction. Therefore, every motion is assumed to be a potential PIO. Calculating the cross correlation between input and output values allows to find the point in time of highest correlation. This time offset $t_{\rho,\max}$ is supposed to be proportional to phase lag. Both parameters are connected by the oscillation frequency ω_{osc} that is estimated by the time difference between adjacent minimum and maximum values. The final relationship between those parameters equals:

$$\Delta\varphi = \omega_{\mathrm{osc}}\, t_{\rho,\max}. \tag{5}$$

To detect a PIO the phase lag between stick deflection and pitch rate must be higher than $\Delta\varphi = 90\,\mathrm{deg}$ and the frequency must be in the range from $1\mathrm{rad}/\mathrm{sec} < \omega_{\mathrm{osc}} < 10\mathrm{rad}/\mathrm{sec}$. For these experiments the limit has been reduced to $\Delta\varphi = 80\,\mathrm{deg}$. This allows to cover also cases were a strong PIO tendency is already present and it allows for some inaccuracy in estimating ω_{osc} and $t_{\rho,\max}$, introduced by the assumptions of the algorithm.

At the same time, all trials with a PIOR of at least 4 have been cross checked against the result of the algorithm. It was assumed that a PIO definetely occurred, if the ratings agree with the indication of the algorithm. If only one of the criteria indicates a PIO, the time traces have been visually checked for PIO occurrence.

6.2 Results

In total 305 trials (60 trials with normal law dynamics, 96 trials direct law dynamics, 149 trials with mode switching) have been collected with the dynamics and the mode switching constellations of Table 2.

The PIO-related dynamics are shown in Table 8. Every cell consists of two entries. The first entry describes the trial with the mode switching, the second entry the stationary tracking task.

	Dynamics								
Pilot	2-D2	2-E4	2-E6	2-E3	2-E8	4-A1	4-E6	4-E3	4-E4
A						✓/×	✓/-	✓/×	
B	✓/-	✓/-	✓/×	✓/✓	✓/✓				
C							✓/×		✓/×
D									
E									
F									
G							✓/×	✓/×	✓/×
H			✓/×	✓/-	✓/✓				
I									
J					✓/✓				

	Dynamics							
Pilot	4-E8	6-E6	6-E5	6-E8	7-E6	7-E4	7-E7	7-E8
A	✓/✓				✓/×	✓/-		✓/✓
B		✓/✓	✓/×	✓/✓				
C	✓/✓		✓/×	✓/×				
D								
E	✓/-	✓/-	✓/×	✓/✓				
F								
G	✓/×						✓/×	
H						×/✓	✓/×	✓/-
I	✓/×				✓/×	✓/×		✓/×
J				✓/✓				

✓ indicates the occurence of a PIO
× indicates that no PIO occured
\- The pilot did not fly this dynamics.

Table 8 Listing of all detected PIO-Events

From the Table 8, it can be stated that two pilots, pilot D and F, never experienced a PIO in any of the trials. Furthermore, there are no normal law dynamics that have been detected as PIO-prone. For the stationary tracking task with the direct law dynamics 12 cases of PIO have been detected. They occurred during at least one period of time during the trial.

After switching, 40 cases of PIOs were detected. In most cases, the PIO tendency was found immediately after the mode switching. In some cases the occurrence was detected only up to 90 sec after the switching.

Seven dynamics have been identified, where a PIO occurs as a consequence of the mode switching: 2-E6, 4-A1, 4-E3, 4-E4, 6-E5, 7-E6 and 7-E7. There are more dynamics that might be added to this group (2-D2, 2-E4 and 4-E6), but one pilot, who discovered a PIO following the mode switching, did not fly the stationary tracking task. That was regarded insufficient to assign the aircraft dynamics to the above group.

Example plots are shown in Figs. 6 and 7. The same pilot flew the same aircraft dynamics (6-E5) in stationary task (Fig. 6) and during mode switching (Fig. 7). Differences are noticeable both in stick deflection and output signal. In the second case the stick deflections are larger and the aircraft is more oscillating around the command value. Directly after mode switching at $t = 48$ sec, high alternating amplitudes in pitch attitude can be observed and a phase lag of $\Delta\varphi = 90\,\text{deg}$ has been determined.

Besides, the pilot rated the aircraft differently. In the first case he assigned a PIOR 2 and emphasized that its handling is very good for a direct law. In the second case he assigned a PIOR 4 and pointed out that overshoots easily occur, if he flies more aggressively. According to the pilot statement oscillations definitely occurred during the trial.

7 Summary and Conclusions

A wealth of data has been generated by the presented simulator campaign. Different types of pilot behaviour have been observed, from fine-tracking over relay-like behaviour up to adaptation to sudden changes in aircraft dynamics.

Although the analysis is still ongoing, the presented experimental approach can be considered successful in revealing tendencies of Category 3 PIOs in fixed-base research station. Every aircraft dynamics and every mode switching constellation was flown by several pilots. Seven switching constellations have been found where PIO tendencies were discovered only after a mode switching occurred. Those dynamics are the most interesting cases for further analysis.

The following conclusions regarding the experimental approach can already be drawn:

1. The experimental setup with its structure and flying task is very promising. Similar experiments, should be conducted the same way. Points for modification

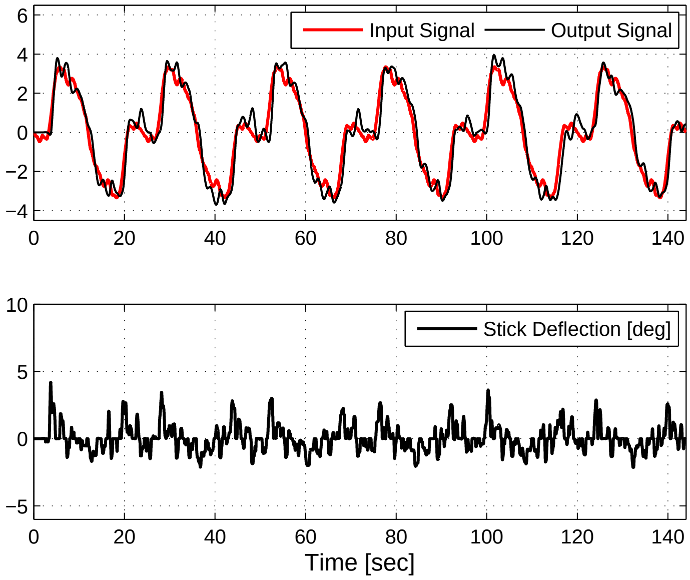

Fig. 6 Pilot B, direct law dynamics 6-E5, stationary flying task (no switching occurred)

might be the duration of the flying task, the ratio of normal law trials compared to mode switching trials in the switching block and a discrete command signal.

2. The evaluation of the direct law dynamics was limited in number of configurations and repetitions. A more detailed campaign should be performed to evaluate all direct law dynamics.
3. The evaluation of initial attitude response, predictability of final response and control sensitivity by the pilots was very helpful in obtaining comments on each aircraft dynamics. It helped the pilots to describe deficiencies of the dynamics. For better evaluation in future experiments, the development of a more normative scale for those parameters should be considered.
4. Most pilots were not familiar with any of the rating scales. Therefore, the detailed discussion of the scales during the briefing and the test examples in the training block were perceived as very helpful. Nevertheless, for future simulator campaigns with pilots who are not familiar with rating scales, a minimum number of three or more different aircraft dynamics might be a better choice for practicing the evaluation process.
5. The used sidestick was not ideal for the experiments. On the other side, its limited deflection range during the trials can be regarded as a type of carefree handling function that is lost in consequence of mode switching.
6. The transient failure rating scale was fully accepted by the pilots. They had no difficutlies rating the transitions. One test pilot remarked that an intermediate rating between TFR 1 and 2 might be helpful. That rating would be inserted in the

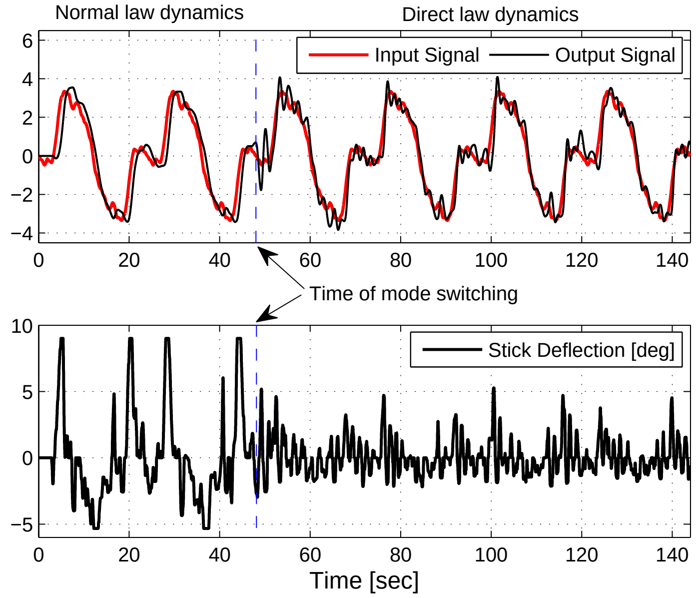

Fig. 7 Pilot B, Mode switching from normal law dynamics NL6 to direct law dynamics 6-E5

degradation branch and would refer to desired performance and moderate pilot compensation. For the conducted test campaign it was not considered necessary, since failure cases were investigated. Nevertheless, the scale might be expanded when used for the evaluation of task-tailored or multi-mode manual flight control systems.

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