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New Flight Simulator Experiments on Pilot-Involved Oscillations due to Rate Saturation

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The generation of a new database concerning pilot-involved oscillations (PIOs) due to rate saturation in modern flight control systems is described. Extensive experiments were carried out on a ground-based flight simulator with five experienced test pilots. Aircraft models from three lateral databases (United States in-flight simulation programs on NT-33 and YF-16) were evaluated. A total number of 342 simulator runs was performed. The simulation results are presented with respect to the effects of the two different pilot tasks, the effects of the simulator motion system, and the different pilot characteristics. The simulation data are analyzed with respect to the new nonlinear PIO prediction criterion developed at the German Aerospace Center, the open-loop onset point (OLOP) criterion. Pilot models were approximated to the measured data and used to validate the OLOP criterion. Finally, the consequences for the OLOP criterion are discussed.

Nomenclature

$A_0(\omega)$	= open-loop amplitude
F_{as}	= roll stick force
$F_{fas}^{\Phi}(j\omega)$	= frequency response from stick force to bank angle
$F_{u_c}^{u_{\mathrm{rle}}}(j\omega)$	= closed-loop frequency response from the closed-loop system input to the rate limiter input
$F_0(j\omega)$	= open-loop frequency response
K_{pil}	= pilot gain
PR_{180}	= phase rate at −180 deg phase angle
p	= roll rate
R	= maximum rate of the limiter
u_c	= closed-loop system input signal
$\hat{u}_c$	= maximum input amplitude
u_{OLOP}	= input signal for open-loop onset point (OLOP) determination
u_{rle}	= rate limiting element input signal
u_0	= input amplitude
y_{OLOP}	= output signal for OLOP determination
ζ	= damping ratio
Φ	= bank angle
Φ_{cmd}	= commanded bank angle
Φ_{cr}	= crossover phase angle
$\Phi_0(\omega)$	= open-loop phase angle
ω	= frequency
ω_{cr}	= crossover frequency
$\hat{\omega}_{\mathrm{onset}}$	= rate limiter closed-loop onset frequency

Introduction

THE high demands on performance and handling qualities of modern aircraft within a large flight envelope require the use of complex electronic flight control systems (FCSs). Especially for highly maneuverable military aircraft, this control technology has opened completely new opportunities for optimization providing benefits in flight performance up to nearly 20%. In the civil aircraft branch, the use of modern electronic FCSs provides a large potential for improvements, such as increased flight safety and reduced pilot workload. However, in spite of all of these benefits, a significant handling qualities problem has come up again with the introduction of electronic FCSs: pilot-involved oscillations (PIOs), also known as pilot-induced oscillations and pilot-in-the-loop oscillations, or aircraft-pilot coupling.

A PIO can be considered as a closed-loop destabilization of the aircraft–pilot loop.[1] A significant correlation was found between PIO incidents reported during the complete history of aviation and rate saturation in FCSs.[2] Nearly all catastrophic PIO cases were associated with rate saturation, such as the crashes of the YF-22 in 1992 and two JAS-39 prototypes in 1989 and 1993. In the past, most PIO cases occurred within the fighter aircraft branch, but also civil airliners with electronic FCSs have demonstrated PIO problems.

In spite of the very strong correlation between PIO susceptibility and rate limiting, no design criteria are established that address nonlinear rate saturation effects. This deficiency in the design requirements was the background for starting a cooperative research project between the DLR, German Aerospace Center, and the FFA, Aeronautical Research Institute of Sweden. The final goal of the project was to validate a new nonlinear PIO prediction criterion proposed by DLR, the open-loop onset point (OLOP) criterion.[3–5] It was aimed at validating the OLOP criterion by utilizing available aircraft models of PIO prone configurations and specific rate limiting experiments that were to be carried out on FFA's research flight simulator (Forskningssimulator) FOSIM.

Prior to conducting the flight simulator experiments, extensive preparations and numerical analyses were performed to optimize the efficiency of the experiments. The following procedure was applied: 1) implementation of lateral databases on personal computers, 2) linear PIO analysis using existing criteria,[6] 3) selection of representative aircraft models and extension to rate limiters in the FCSs, 4) nonlinear PIO analysis using OLOP,[7–9] 5) development of an interface Simulink®–FOSIM using automatic C-code generation,[10] 6) definition and optimization of a flight-test program and high-gain tracking tasks,[11,12] 7) conduction of simulator experiments on FOSIM in May and August 1997, and 8) data analysis, validation of the OLOP criterion, and identification of pilot behavior.

Five experienced test pilots from Wehrtechnische Dienststelle 61 (WTD-61), DLR, Försvarets Materielverk (FMV), and SAAB took part in the experimental phase. A large database on PIO due to rate saturation in the roll axis was generated. The analyses presented in this paper focus on the validation of the OLOP criterion.

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PIO Categories

For the understanding and analysis of PIO, the following classification was recently introduced.[13] The three PIO categories may be characterized as follows: Category I, essentially linear pilot–vehicle system oscillations; Category II, quasi-linear pilot–vehicle system oscillations with rate or position limiting; and Category III, essentially nonlinear pilot–vehicle system oscillations with transitions.

The main effects causing Category I PIO are identified as excessive lags mainly caused by time delays and various digital filters in the FCS. These problems can be predicted by the established frequency-domain criteria, such as those by Neal and Smith,[14] Smith and Geddes,[15] Gibson,[16] and Hoh.[17]

It is very difficult to predict Category III problems, but a very promising Category II PIO prediction criterion was developed at DLR based on the describing function technique, the OLOP criterion.[3–5]

OLOP Criterion

Background

By analyzing different systems with the describing function technique, it was observed that the location of the rate limiter onset point in a Nichols chart is highly correlated with the severity of the corresponding jump phenomena in the quasi-linear frequency response of the closed-loop system.[4] The observed phase jump leads to a dramatic loss of phase and amplitude margin indicating the potential for an instability of the closed-loop system. Therefore, the OLOP location is a measure for the magnitude of the additional time delay due to the rate limiting.

Definition

The OLOP is defined as the frequency-response value of the open-loop aircraft or aircraft–pilot system at the closed-loop onset frequency $\hat{\omega}_{\text{onset}}$ that is defined as the frequency at which the rate limiter is activated first time for closed-loop conditions under maximum pilot input amplitude $\hat{u}_c$ (worst case). With the use of the following equation, $\hat{\omega}_{\text{onset}}$ is determined:

$$\hat{u}_c \cdot \left| F_{u_c}^{u_{\text{rle}}}(j\hat{\omega}_{\text{onset}}) \right| = R/\hat{\omega}_{\text{onset}} \tag{1}$$

This determines the intersection of the frequency-response amplitude $\hat{u}_c \cdot |F_{u_c}^{u_{\text{rle}}}(j\omega)|$ (from the input of the closed-loop system u_c to the input of the rate limiter u_{rle}) and a straight line with a slope of -20 dB/decade that crosses the 0-dB line at the maximum rate of the limiter R.

Determination

For the determination of the OLOP criterion, the use of the describing function technique is not necessary. Only a linear model of the aircraft including the FCS must be available. The procedure for the evaluation of the OLOP criterion is summarized as follows.

1) Define a simple (high) gain pilot model based on *linear* aircraft dynamics.

2) Calculate the *linear* closed-loop frequency response from the stick input to the input of the rate limiter $F_{u_c}^{u_{\text{rle}}}(j\omega)$.

3) Determine the closed-loop onset frequency $\hat{\omega}_{\text{onset}}$ considering stick and control surface limits [Eq. (1)].

4) Calculate the required open-loop frequency response $F_0(j\omega)$ and separate into amplitude $A_0(\omega)$ and phase angle $\Phi_0(\omega)$.

5) OLOP is equal to $[\Phi_0(\hat{\omega}_{\text{onset}}), A_0(\hat{\omega}_{\text{onset}})]$.

Steps 1 and 4 are examined further in detail.

Step 1: Pilot Model

The pilot model has to be adjusted to the linear aircraft model, which means that the pilot has adapted to an aircraft behavior without rate saturation. It is assumed that in a time period after rate limiting onset the pilot dynamics remain those adapted to the linear aircraft behavior (posttransition retention).[13] The sudden change in closed-loop aircraft behavior can lead to a strong misadaptation of the pilot that can cause an instability of the closed-loop aircraft–pilot system (PIO).

It is recommended that simple gain pilot models be used because the pilot usually reacts as a simple gain during fully developed PIO (synchronous precognitive behavior).[13] The pilot gain $K_{\text{pil}}(\Phi_{\text{cr}})$ is adjusted based on the linear crossover phase angle of the open-loop aircraft–pilot system Φ_{cr}, for example, for the roll axis (in decibel),

$$K_{\text{pil}}(\Phi_{\text{cr}}) \cdot \left| F_{fas}^{\Phi}(\omega_{\text{cr}}) \right| = 0 \tag{2}$$

For the evaluation of the OLOP criterion, a gain spectrum from $\Phi_{\text{cr}} = -120$ deg (low pilot gain) up to $\Phi_{\text{cr}} = -160$ deg (high pilot gain) should be applied. This gain spectrum can be used to investigate a pilot gain sensitivity.

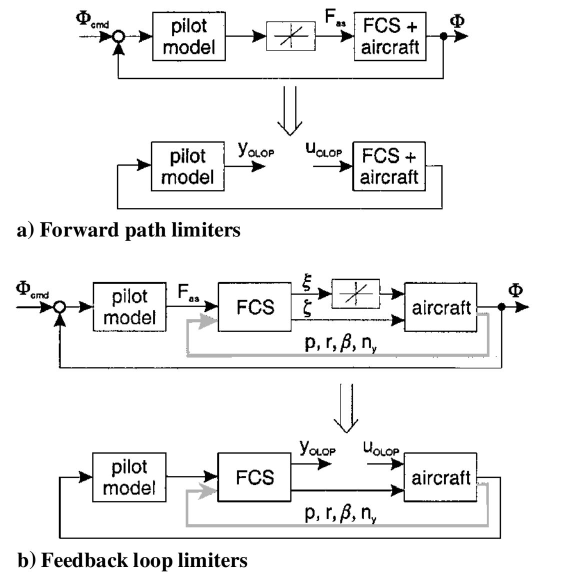


Fig. 1 Open-loop frequency response of aircraft–pilot systems for determination of OLOP.

Step 4: Open-Loop Frequency Response

The required open-loop frequency response $F_0(j\omega)$ is determined by cutting the system at the rate limiter and treating the system with a removed rate limiter: The output of the rate limiter is defined as the input of the open-loop system u_{OLOP}; the input of the rate limiter is defined as the output of the open-loop system y_{OLOP} (Fig. 1). This procedure is applicable to the two typical rate limiter locations (forward path or feedback loop).

The OLOP criterion can be evaluated for two cases: with or without the pilot closing the loop. This corresponds to the two possibilities of instability: The aircraft system (including FCS) can become unstable when the rate limiter is activated (for basically unstable aircraft[5]) and the aircraft–pilot system can become unstable when the rate limit is reached and the pilot is in closed-loop control.

OLOP Boundary

The obtained OLOP value has to be compared to the OLOP boundary defined in a Nichols chart (Fig. 2). This boundary had been verified by evaluating several different configurations from three roll axis databases (LATHOS,[18] F-18,[19] and YF-16[20]).

The aircraft models from the LATHOS database were extended to rate limiters in the forward path of the FCSs. The F-18 and YF-16 aircraft models were used to examine the effects of rate limiting in the feedback loop of the FCSs.[7–9]

A high correlation between the OLOP criterion and the Category II PIO potential was found based on nonlinear off-line simulations with pilot models. These investigations indicate that the OLOP criterion is applicable to both forward path and feedback loop rate limiters using the same PIO boundary. However, the feedback loop limiters provide a much stronger Category II PIO potential, especially for high feedback loop gains. Category II PIO due to rate limiters in the forward path is mainly possible for very high pilot gains or extremely low maximum rates.

New Experimental Investigations

In January 1995, DLR and FFA entered into a 3-year collaborative project with the purpose of validating the OLOP criterion. Experimental investigations on FOSIM were scheduled. The results of the simulation campaign on FOSIM in May and August 1997 are presented next.

Table 1 Performance of FOSIM's motion system

Motion	Excursion	Velocity	Acceleration
Pitch	−7 to +14 deg	8 deg/s	66 deg/s^2
Roll	±17 deg	10 deg/s	66 deg/s^2
Heave	±0.3 m	±0.3 m/s	−10 to +3 m/s^2

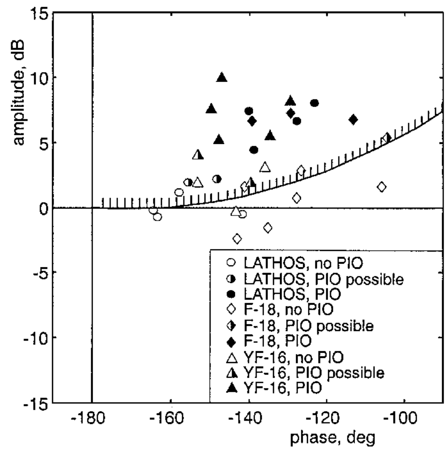


Fig. 2 Verification of the OLOP boundary.[8]

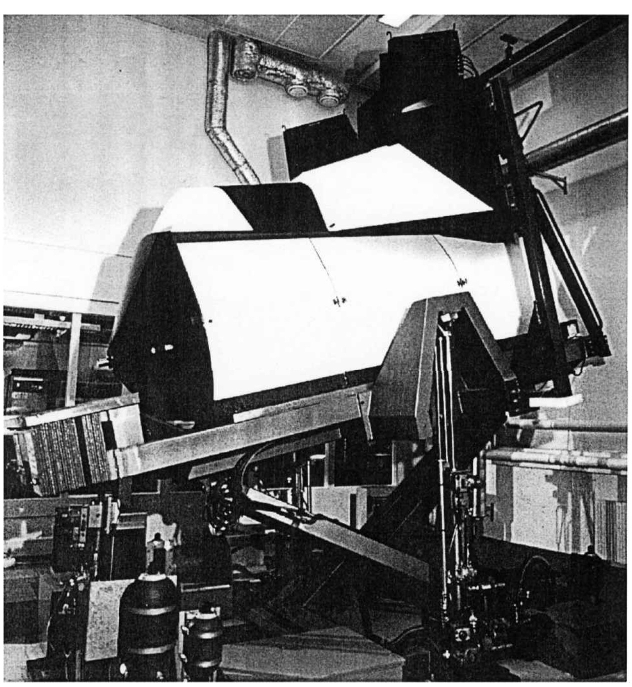


Fig. 3 FFA's flight simulator FOSIM.

FOSIM

FFA's ground-based research flight simulator FOSIM was used for the experimental PIO investigations (Fig. 3). Its motion system is a three degree-of-freedom system in roll, pitch, and heave with performance shown in Table 1.

The mean total time delay in the path from stick input to the output in the visual system and head-up display (HUD) was measured to about 50 ms. The stick used for the tests was a JAS-39 stick, a prototype of the stick used in the production aircraft. The feel system of this stick is a spring and damping. The stick forces correspond approximately to the forces assumed in the aircraft models. The HUD graphics generator used in FOSIM is an EP-12, the type used in the JA-37 Viggen fighter. An actual wide-angle HUD is used. The preferred visual system used for flight dynamic tests is a Tector single window hybrid analog/digital system. The advantage with these devices is that they have a shorter time delay than most modern digital equipment.

Interface Simulink–FOSIM

To transfer Simulink models into the flight simulator FOSIM it was decided to use Simulink Real-Time Workshop (RTW) for an automatic C-code generation. RTW and the simulator specific software have been adapted so that the process of transferring Simulink models into the simulator environment is almost entirely automatic. This is an exciting technique that provides great productivity gains in the development of flight simulation models and great flexibility regarding aircraft model changes during simulation campaigns.

Experiment Design and Conduction

Definition of Aircraft Models

To validate the OLOP criterion a large number of aircraft models from the three databases (LATHOS,[18] F-18,[19] and YF-16[20]) has been evaluated. Some representative configurations were selected from these databases and were extended to rate limiters in the forward path and the feedback loop of their roll axis FCSs, respectively. The maximum rates of the limiters were defined to cover a wide spectrum of the OLOP criterion. Configurations with different Category I PIO characteristics were purposely selected to study the relationship between Categories I and II PIO.

In comparison to the former numerical investigations[6,7] some modifications on the FCSs were introduced to obtain a similar roll performance and to compensate for the simulator time delay of 50 ms (Ref. 21). Table 2 presents the selected configurations.

Two basic configurations from each database were selected for simulator testing. The file indices L1 to Y2 will be used subsequently. In Fig. 4, the roll rate step responses for the maximum stick force of 80 N are presented.

All aircraft models have a similar roll performance, but the YF-16 models are characterized by an extremely adverse roll behavior. A roll oscillation with poor damping ($\zeta \approx 0.3$) occurs, and the roll rate returns to zero after about 10 s, although the roll stick is still fully deflected. An explanation for this very strange roll behavior might be that the linear YF-16 model used was only valid in the ground effect. It is obvious that no pilot would like this behavior; nevertheless, it was decided to evaluate the YF-16 configurations on FOSIM.

In Table 3 the basic configurations to be evaluated and the maximum rates of the limiters are summarized. Their PIO characteristics

Table 2 Selected configurations

Database	Configuration	Index
LATHOS	L3_2	L1
LATHOS	L2_1T4	L2
F-18	1_0	F1
F-18	B1	F2
YF-16	INI	Y1
YF-16	MOD	Y2

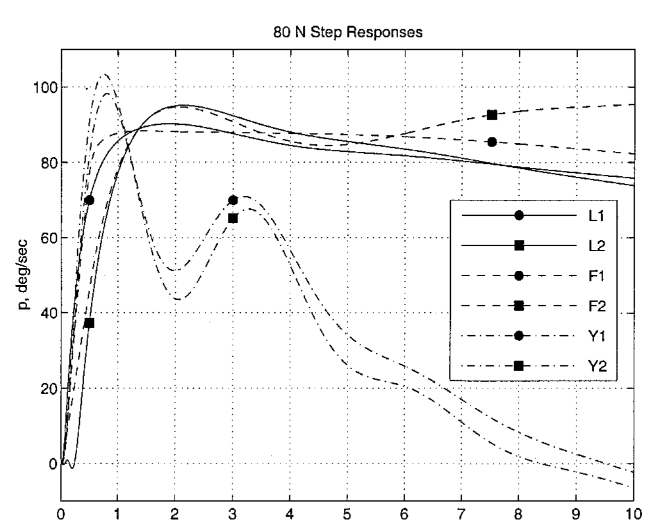
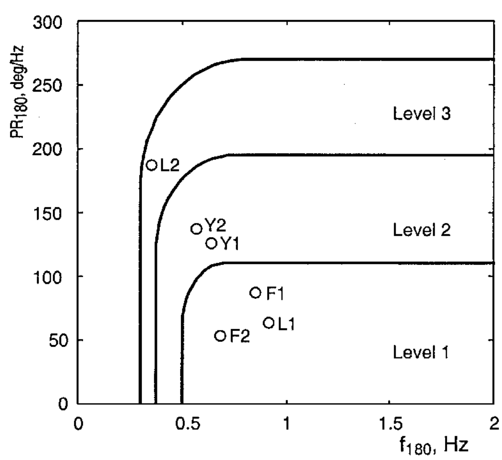


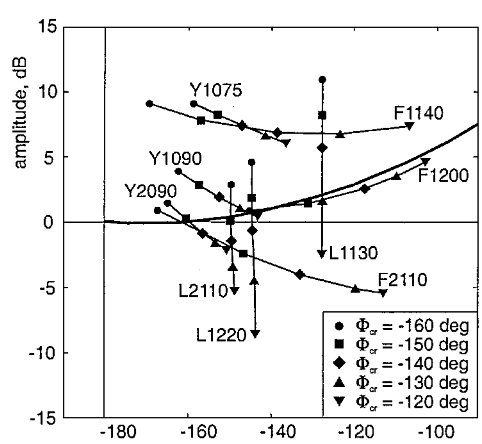
Fig. 4 Roll rate step responses of the selected configurations.

Table 3 Configuration summary

Index	Maximum rate	Extended index	Comments/expectations
L1	130 N/s	L1130	No Category I PIO, rate limiter in the forward path, clear Category II PIO potential for high pilot gains predicted.
L1	220 N/s	L1220	No Category I PIO, rate limiter in the forward path, little Category II PIO potential for high pilot gains predicted.
L2	110 N/s	L2110	Strong Category I PIO, rate limiter in the forward path, little Category II PIO potential for high pilot gains predicted.
F1	140 deg/s	F1140	No Category I PIO, rate limiter in the feedback loop, strong Category II PIO even for low pilot gains predicted.
F1	200 deg/s	F1200	No Category I PIO, rate limiter in the feedback loop, no Category II PIO predicted.
F2	110 deg/s	F2110	No Category I PIO, rate limiter in the feedback loop, little Category II PIO potential for high pilot gains predicted.
Y1	75 deg/s	Y1075	Medium Category I PIO, but adverse roll behavior, rate limiter in the feedback loop, strong Category II PIO even for low pilot gains predicted.
Y1	90 deg/s	Y1090	Medium Category I PIO, but adverse roll behavior, rate limiter in the feedback loop, Category II PIO potential predicted.
Y2	90 deg/s	Y2090	Medium Category I PIO, but adverse roll behavior, rate limiter in the feedback loop, Category II PIO potential for high pilot gains predicted.



a) Phase rate (category I)



b) OLOP (category II)

Fig. 5 PIO characteristics of the defined configurations (including 50 ms time delay of the simulator).

are shown in Fig. 5 utilizing the phase rate criterion (Category I) and OLOP criterion (Category II).

In both criteria the additional time delay of the simulator (50 ms) is considered. In the OLOP criterion, a pilot model gain spectrum is considered (crossover phase angles from $\Phi_{cr} = -120$ to -160 deg). This gain spectrum elucidates the pilot gain sensitivity of each configuration. For example, L1130 is located in the critical area only for high gains and relocates directly into the safe area when the pilot reduces the gain. F1140, on the other hand, even for low gains is located in the critical area and, therefore, is prone to PIO due to rate saturation for all gains.

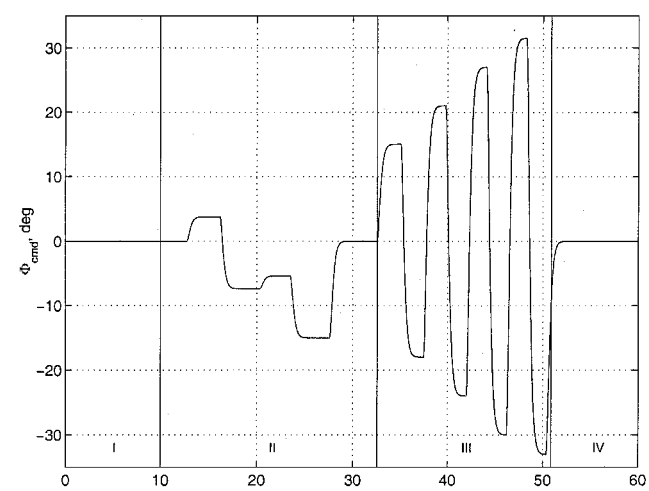


Fig. 6 Time sequence for the HUD tracking task.

Tracking Tasks

Two pilot tasks have been defined prior to the test runs, one tracking task in the HUD and one aiming task in the simulator's visual system: For the first task, HUD, the pilot has to track a commanded bank angle that is displayed on the HUD. The second task is a ground attack test technique[22] (GRATE). Both tasks have been optimized during two simulator test sessions.

The HUD task induces only roll maneuvering and provides data that are fairly easy to analyze. Figure 6 shows the time sequence of the commanded roll angle Φ_{cmd} that is dependent on the onset frequency of the rate limiter. It is separated into four segments: In the first segment, the pilot has the possibility to give some open-loop inputs to the aircraft (about 10 s, no task). The second segment starts a low demanding roll axis task (stochastic) to give the pilot a feeling about the closed-loop control of the aircraft. The third segment increases the task demands (frequency and amplitude) depending on the closed-loop onset frequency. Maximum stick force and rate limiting onset are expected in this segment. In the fourth segment Φ_{cmd} is set to zero to recognize whether a PIO (limit cycle) builds up.

Figure 7 presents the pilot's view of the GRATE task. Five triangles, placed abreast to make the task mainly lateral, are drawn on the HUD as targets. The lateral distance between the targets is 50 m. Only one of the five triangles is lit at a certain time such that a sequence is generated. The pipper is fixed in the HUD and must be aimed at the target that is currently lit.

The time sequence of the GRATE task was changed stochastically during the experiments and was not adapted to each configuration. More effort had been spent on the definition of the HUD tasks, because the test runs had shown that it is better suited for evaluating the roll axis characteristics.[11]

Procedure

Five experienced test pilots took part in the simulation campaign. Three had a military/fighter aircraft background; two had mainly transport aircraft experience. Each pilot, except one who only did the HUD task, flew nine configurations, multiplied by two tasks, multiplied by two (motion on or off), multiplied by two (rate limit on or off), for a total of 72 runs.

The experiment procedure started with a pilot briefing. The background for the experiments was illustrated, and the two tasks were explained. All pilots were asked to follow the command bar in the HUD task as accurately and quickly as possible and to fly as aggressively as they would do in real flight, although this is obviously a very difficult job. The pilots were asked to assess their gain. For the GRATE runs, the pilots were asked to try to filter out the roll axis characteristics.

Before starting the experiments the simulator handling was explained to the pilots by the FOSIM engineers. Then some test runs for a familiarization with the simulator and the tracking tasks were carried out.

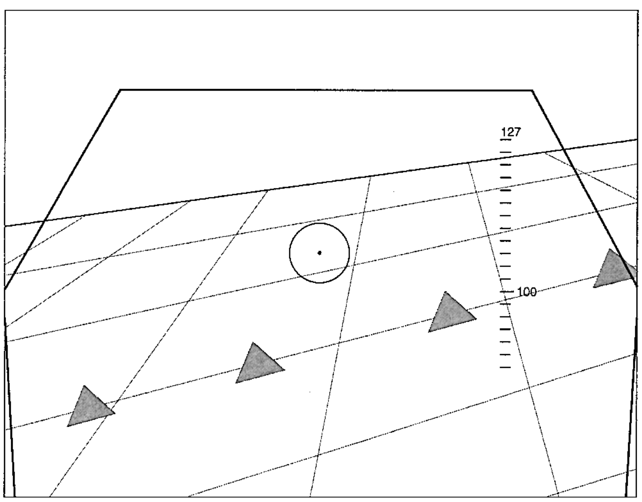


Fig. 7 GRATE task as seen from the cockpit.

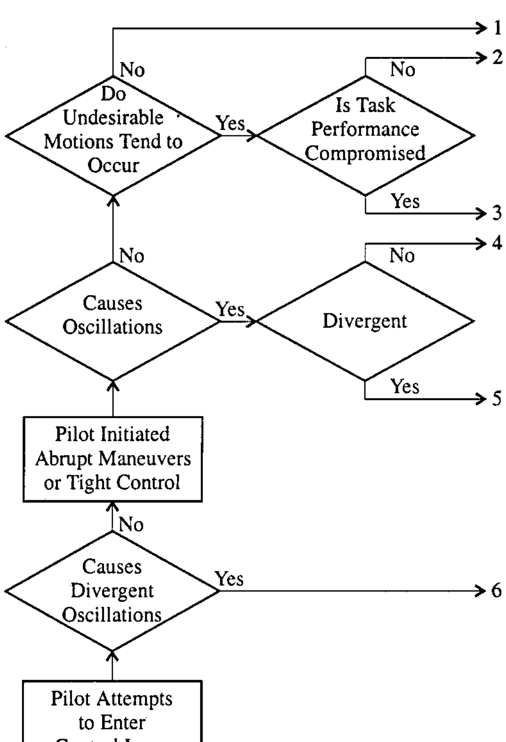
The entire program was separated into four sessions: HUD without motion, HUD with motion, GRATE without motion, and GRATE with motion. Between these sessions the pilots had the opportunity to take a break. After each run the pilots were asked for comments and pilot ratings according to the PIO rating scale (Fig. 8). At the end of the four sessions the pilots were asked for their general comments, and some special topics were discussed. For some interesting cases, the time histories were presented to the pilots during the debriefing.

Simulation Results

In all, 342 runs were carried out. The following observations were made. PIO ratings (PIOR) given by the different pilots have to be considered carefully due to different interpretations of the PIO rating scale and its highly nonlinear character. It is sometimes hard for a pilot to distinguish between oscillations and undesirable motions. The main distinction is between PIOR 3 and 4. Similar problems with the scale were reported in Ref. 23. However, some of the PIO ratings given in these experiments have to be considered as wrong. Ratings are subjective, depending on the pilots' momentary physical and mental condition, their familiarization with the simulator and the task, etc. The detection of wrong ratings in these experiments was possible because several pilots participated and because several design criteria and a suitably defined task performance parameter were used.

The HUD task was judged to be better suited for evaluating the roll axis characteristics than the GRATE task. With GRATE it was sometimes difficult for the pilots to filter out the roll axis characteristics due to significant roll–yaw cross couplings. Furthermore, the GRATE task is highly dependent on pilot technique and was not specifically adapted to each configuration. This led to several cases in which the full stick force and the rate limit were not reached. However, also for the GRATE task fairly consistent ratings were achieved.

No clear tendency was found regarding the effect of the motion system on the PIO potential. A reason for this observation might be the low performance of the motion system so that the motion cues are too small. To solve this problem, further experiments on other flight simulators with more powerful motion systems or in-flight experiments are required.



Description	#
No tendency for pilot to induce undesirable motions	1
Undesirable motions tend to occur when pilot initiates abrupt maneuvers or attempts tight control. These motions can be prevented or eliminated by pilot technique.	2
Undesirable motions easily induced when pilot initiates abrupt maneuvers or attempts tight control. These motions can be prevented or eliminated but only at sacrifice to task performance or through considerable pilot attention and effort.	3
Oscillations tend to develop when pilot initiates abrupt maneuvers or attempts tight control. Pilot must reduce gain or abandon task to recover.	4
Divergent oscillations tend to develop when pilot initiates abrupt maneuvers or attempts tight control. Pilot must open loop by releasing or freezing the stick.	5
Disturbance or normal pilot control may cause divergent oscillation. Pilot must open loop by releasing or freezing the stick.	6

Fig. 8 PIO rating scale.

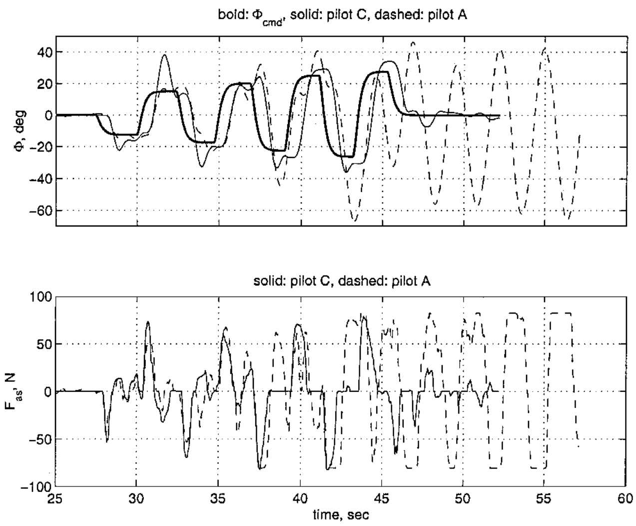


Fig. 9 Examples of open-loop (pilot C) and closed-loop (pilot A) control behavior.

Very different pilot behaviors were observed. The fighter pilots gave the most consistent ratings and fulfilled the expectations mostly due to their aggressive behavior. They represent a kind of worst-case behavior with respect to PIO, whereas the transport pilots seem to be more focused on flight safety instead of detecting flying qualities problems. Even an open-loop control technique was observed: Figure 9 presents a comparison between two HUD runs of transport pilot C and fighter pilot A with a highly PIO prone configuration (F1140). Pilot A got into a sustained oscillation due to his closed-loop control, whereas pilot C did not run into problems. It can be seen that after 37 s simulation time, pilot C only performed pulse-like inputs with zero stick force in between (open-loop behavior).

The different pilots exhibited different levels of sensitivity to rate saturation, for example, one of the fighter pilots reacted extremely sensitively. However, the importance of having several test pilots with different control characteristics in a simulation campaign was confirmed.

PIO due to rate saturation in the forward path appears to be much more controllable than PIO due to rate saturation in the feedback loop. For example, no severe PIO occurred for configuration L1130, although its OLOP parameter is located clearly in the critical OLOP area for high pilot gains (Fig. 5). The gain spectrum considered leads to an almost vertical line in the OLOP diagram for configurations with rate limiters in the forward path. This means that a pilot can quite easily leave the critical area by reducing the gain.

Some unexpected nonlinear PIO cases occurred for configurations with rate limiters in the feedback loop due to very aggressive pilot behavior. These will be addressed in the analysis section.

Data Analysis

Pilot Model Identification

For the evaluation of the OLOP criterion, a simple gain pilot model is required. The well-defined HUD task allowed an identification of the pilot behavior because the input and output signals of the pilots were available. For this purpose off-line simulations of the closed-loop aircraft–pilot system utilizing a simple gain pilot model were carried out for all HUD runs. The commanded roll angle time sequences Φ_{cmd} from the flight simulator experiments were used as input signals to the aircraft–pilot model loops (Fig. 10).

An iterative method was applied to determine a suitable pilot model gain, which represents the actual pilot behavior as closely as possible. The expression suitable does not mean that it was aimed at achieving the best matching between the pilots and the pilot models. The goal was to get a similar character of the simulated aircraft–pilot model compared to the experiments in terms of the aircraft–pilot loop stability, such as overshoots, oscillations, and task performance.

The iteration minimized the difference in the roll angles between piloted and off-line simulations. This numeric determination provided fairly suitable results in most cases. However, all runs were checked as to if the same character was obtained as discussed earlier. In some cases high-frequency oscillations in the experimental time histories were approximated by rather smooth curves. In these cases, the determined crossover phase angles Φ_{cr} were adjusted manually. With these gains, each run could be located in the OLOP diagram.

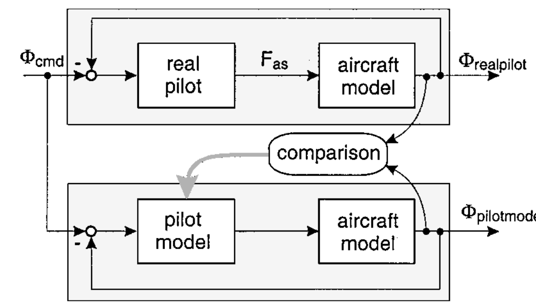


Fig. 10 Determination of pilot model gains.

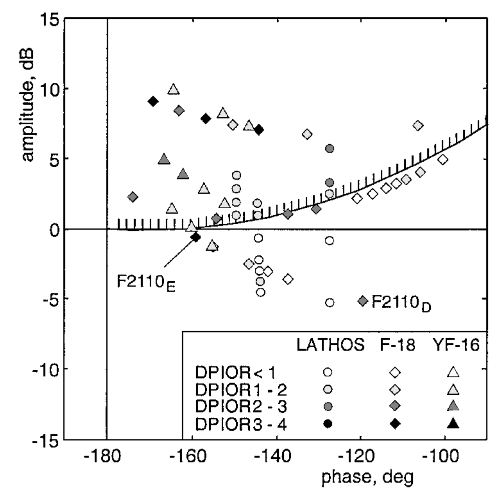


Fig. 11 Validation of the OLOP criterion with FOSIM data.

Validation of the OLOP Criterion

For the validation of the OLOP criterion the differences between the PIO ratings of nonlinear and linear runs have to be considered because OLOP only predicts possible problems due to rate saturation. Therefore, the following rating difference parameter was defined:

$$\mathrm{DPIOR} = \mathrm{PIOR}_{\mathrm{nonlinear}} - \mathrm{PIOR}_{\mathrm{linear}} \tag{3}$$

Additionally, a task performance parameter was calculated, which helped to solve some of the problems with the PIO rating scale.[21]

By the use of the pilot model gains and the DPIOR parameter, Fig. 11 was generated. It shows a good correlation between the prediction of the OLOP criterion and the resulting pilot ratings. For those points that do not correlate as expected, the following reasons were identified.

The transport pilots generally used a low gain and sometimes even performed an open-loop control. With this behavior, they often did not run into problems because of the rate limitation and their DPIOR was small.

The YF-16 configurations are already bad in the linear case and suffer from roll–yaw cross couplings. Rate limiting does not lead to further significant degradation; thus, DPIOR is small.

Some configurations exhibit a high sensitivity to pilot gain, which means that already a small deviation between the pilot model gain and the actual pilot can cause the OLOP to be unfavorably located for the validation in Fig. 11. This is the case for configuration F2110 flown by pilot E ($F2110_E$ in Fig. 11).

As explained earlier, the ratings are subjective, and some of them have to be considered as wrong. This is particularly true for the point marked $F2110_D$ in Fig. 11. The corresponding time histories do not show any significant difference between the linear and the nonlinear runs, nor does the task performance parameter, nevertheless the pilot assigned different ratings.[21]

Consequences for the OLOP Criterion

The main finding is that the PIO potential due to rate saturation in the feedback loop is even higher than expected. It was discovered that for some configurations with rate limiting in the feedback loop clear PIO cases occurred in the experiments, although the OLOP criterion did not predict PIO problems that clearly; the OLOP parameters of those configurations were located around the boundary. Furthermore, it was confirmed that rate saturation in the forward path is less critical than in the feedback loop even for similar OLOP locations. Most likely, the change in the system dynamics caused by forward path rate limiting is more understandable for the pilot. This is confirmed by the observation that for configurations with rate limiting in the forward path no significant increase of the identified pilot model gains due to rate saturation was found. Instead, for the configurations with rate limiting in the feedback loop, the pilot model gains for the nonlinear runs are significantly higher than for the linear runs.[21]

This discrepancy indicates that two different OLOP boundaries are required depending on the location of the rate limiter (forward path or feedback loop). However, it is proposed to retain only one boundary, but with relaxation for the rate limiting in the forward path and the recommendation to keep a safety margin to the OLOP boundary for systems with rate limiters in the feedback loop. Therefore, experience and engineering judgment is still required for the application of the OLOP criterion. It has to be proved in the future by application to a large spectrum of different vehicles (fighter, transport, helicopter, etc.) to develop a real cookbook with exactly defined application rules.

Lessons Learned

1) The conscientious preparation of the experiments and optimization of the simulation setup and, especially, the pilot tasks is extremely important to obtain representative results.

2) The use of automatic code generation tools is an important issue to increase efficiency. It has been proven to be a great success within this project.

3) A numerical analysis of the configurations in advance is recommended; it helps in understanding the effects observed during the experiments.

4) It is recommended to involve several pilots with different backgrounds in a simulation campaign and to repeat runs. This helps to identify and to remove significantly wrong ratings.

5) Simulation data have to be considered carefully, such as an open-loop pilot behavior during a closed-loop task. The pilot briefing is an important issue, even experienced test pilots need some time for familiarization with the simulator and the tasks.

Conclusions

Flight simulator experiments were carried out to study the effects of rate saturation in modern FCSs in the roll axis. A simulation campaign with five experienced test pilots was conducted. All test runs were executed with and without the simulator motion system activated. Two different pilot tasks were used, and all runs were performed with and without rate limiting leading to 342 simulator runs.

Extensive data analysis was carried out aiming at the validation of the OLOP criterion, a new criterion for nonlinear PIO problems. Based on these investigations the following conclusions can be drawn.

1) A high correlation was found between the predictions of the OLOP criterion and the pilot ratings. Therefore, the OLOP criterion has been proven to be a suitable tool to predict the Category II PIO potential of new aircraft. It can be applied in the design phase of new FCSs.

2) Experience is required for interpreting the predictions of the OLOP criterion. It has been shown that rate limiting in the feedback loop is significantly more critical than forward path rate limiting. The OLOP criterion can not be considered as a cookbook, the designer must have background knowledge.

3) The effects of the motion cues in the roll axis are not fully understood. In these specific experiments no general trend was found, that is, no difference was identified between the PIO susceptibility with and without motion system activated. Flight tests are required for clarification.

The analyses presented herein were focused on the validation of the OLOP criterion. However, the generated database has a great potential for further analyses, such as the testing of real-time PIO detection algorithms or the use of more sophisticated methods for pilot model identification.

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