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Simulator Evaluation of New Experimental Techniques for Aircraft Pilot Coupling Susceptibility Assessment

M.H. Smaili

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ABSTRACT
The introduction of active control technology and modern, full authority, fly-by-wire (FBW) systems demonstrated an increase of adverse interactions between the human pilot and aircraft dynamics. This phenomenon, also known as Aircraft Pilot Coupling (APC) or Pilot-in-the-Loop Oscillations (PIO), can result into major aircraft handling qualities problems or loss of flight control. Recognition of handling qualities deficiencies related to APC/PIO early during the flight control system design process is therefore mandatory. In support of this process, a practical design guideline should be available that provides well established APC/PIO analysis and experimental techniques in order to prove that a highly augmented aircraft is sufficiently free from APC/PIO proneness. To address the industrial needs for such a guideline, the Group for Aeronautical Research and Technology in Europe (GARTEUR), recently established an Action Group on APC/PIO analysis and experimental techniques. An emphasis during this research was to extend the current technologies with new analysis and experimental methods for non-linear APC/PIO (Category II) assessment. This paper presents an overview of the simulator campaign, conducted as part of the project, that focussed on the development of new experimental techniques to evaluate non-linear APC/PIO susceptibility. The effectiveness of the proposed non-linear APC/PIO experimental techniques is evaluated along with some lessons learned during the campaign. Results of the Action Group were presented in a concept handbook, supported by analysis tools, that provides a profound basis towards design of aircraft free of adverse APC/PIO characteristics.

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Summary

The introduction of active control technology and modern, full authority, fly-by-wire (FBW) systems demonstrated an increase of adverse interactions between the human pilot and aircraft dynamics. This phenomenon, also known as Aircraft Pilot Coupling (APC) or Pilot-in-the-Loop Oscillations (PIO), can result into major aircraft handling qualities problems or loss of flight control. Recognition of handling qualities deficiencies related to APC/PIO early during the flight control system design process is therefore mandatory. In support of this process, a practical design guideline should be available that provides well established APC/PIO analysis and experimental techniques in order to prove that a highly augmented aircraft is sufficiently free from APC/PIO proneness. To address the industrial needs for such a guideline, the Group for Aeronautical Research and Technology in Europe (GARTEUR), recently established an Action Group on APC/PIO analysis and experimental techniques. An emphasis during this research was to extend the current technologies with new analysis and experimental methods for non-linear APC/PIO (Category II) assessment. This paper presents an overview of the simulator campaign, conducted as part of the project, that focussed on the development of new experimental techniques to evaluate non-linear APC/PIO susceptibility. The effectiveness of the proposed non-linear APC/PIO experimental techniques is evaluated along with some lessons learned during the campaign. Results of the Action Group were presented in a concept handbook, supported by analysis tools, that provides a profound basis towards design of aircraft free of adverse APC/PIO characteristics.

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Abbreviations

ADMIRE	Aero-Data Model in Research Environment
APC	Aircraft Pilot Coupling
DM	Demonstration Maneuver
FBW	Fly-By-Wire
GARTEUR	Group for Aeronautical Research and Technology in Europe
PIO	Pilot-in-the-Loop Oscillations
STEM	Standard Evaluation Maneuver

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1 Introduction

The development of active control technology and FBW flight control systems (FCS) for modern aircraft initiated an increase of problems encountered in the aircraft man-machine interface. These problems express themselves as adverse interactions between the human pilot and the aircraft dynamics and are indicated as Pilot-in-the-Loop Oscillations or PIO. Formally, PIO can be defined as sustained or uncontrollable oscillations resulting from the efforts of the pilot to control the airplane. Currently, PIO is considered as a subclass of Aircraft-Pilot Coupling or APC as the more general definition for these interactions.

PIO can be considered as a closed-loop destabilisation of the aircraft-pilot loop, triggered by a rich variety of diverse phenomena in terms of effective aircraft dynamics and pilot behavior. In most cases, a PIO event is triggered by a sudden change of the vehicle dynamics during a high demanding flying task in which the pilot is controlling the aircraft tightly and unable to adapt himself. This situation can eventually lead to a loss of flight control in which the aircraft can sometimes only be recovered by opening the aircraft-pilot loop through stick release. Three elements that play an essential part in the APC/PIO phenomenon are the pilot, the aircraft dynamics and the trigger. The trigger can be defined as an event that introduces the adverse interactions between the pilot and the aircraft. Significant APC/PIO triggers can be FCS mode changes, a change of the non-linear behavior of the FCS or a change of pilot behavior (e.g. increase of the pilot gain) caused by disorientation. Especially the introduction of FBW technology has increased the amount of triggers related to FCS mode changes that may induce undesirable APC/PIO characteristics.

The APC/PIO phenomena can generally be classified into three categories based on possible different behavior of the closed-loop pilot-aircraft vehicle system. These classifications are:

- *Category I*
  Essentially linear pilot-vehicle system oscillations. The APC/PIOs in this category result from identifiable phenomena such as excessive time delay, excessive phase loss due to filters, improper control/response sensitivity, etc. As they are the simplest to model, they can be very well understood in order to prevent this class of APC/PIO.

- *Category II*
  Quasi-linear pilot-vehicle system oscillations with rate or position limiting. The closed-loop pilot vehicle system has a non-linear behavior, mainly characterised by the saturation of position or rate limited elements. In particular, rate-limited actuators may cause a sudden change of the aircraft dynamics that contributed to past APC/PIO incidents and accidents

(YF22, Gripen). These APC/PIOs can in general be modeled as linear events in which an identifiable nonlinear contribution may be treated separately.

- *Category III*
  Essentially non-linear pilot-vehicle system oscillations. The closed-loop pilot vehicle system has a highly non-linear behavior, with no further peculiar characteristics. Category III APC/PIOs can be further characterised by transitions in pilot and aircraft behavior such as mode and control method changes (i.e. from attitude to load factor) and multiple axis problems. These APC/PIOs rarely occur and are difficult to recognise. When they do occur, the APC/PIOs in this category are the most severe.

Aircraft handling qualities research throughout the years has established a subset of requirements that can be used in aircraft design and analysis for the prevention of APC/PIO. Due to the significance of the APC/PIO problem, the U.S military authorities have included specific flying qualities requirements for APC/PIO in their Military Standard Specifications[1] since 1982. The concept of PIO detection methods is further emphasised in later issues of this standard[2]. Further research has been conducted in the United States and Europe to better understand the APC/PIO phenomenon and to develop methods and techniques to predict undesirable APC/PIO tendencies[3,4,5].

Although most established APC/PIO criteria were determined to be suitable for the prediction of linear APC/PIOs, a set of criteria to evaluate non-linear PIO phenomena is still under investigation and is not yet adequate enough[5]. In addition, current industry standards lack a consistent practical guideline providing PIO analysis methods and unified experimental techniques to design aircraft sufficiently free of APC/PIO.

2 GARTEUR Action Group

In 1999, the Group for Aeronautical Research and Technology in Europe (GARTEUR) established an Action Group to address the need for the development of a design guideline on APC/PIO analysis and unified experimental evaluation techniques. The action group, designated as Flight Mechanics Action Group 12 (FM(AG12)) 'Pilot-in-the-Loop Oscillations – Analysis and Test Techniques for their Prevention', was established within the framework of the GARTEUR Flight Mechanics, Systems and Integration Group. The project, that lasted two and a half years, was carried out by thirteen partners from six different countries (*table 1).*

Table 1: GARTEUR FM(AG12) project partners

ONERA	Office National d'Études et de Recherches Aérospatiales (France)
CEV	Centre d'Essais en Vol (France)
DA	Dassault Aviation (France)
LAAS	Laboratoire d'Analyse et d'Architecture des Systèmes (France)
FOI	Totalförsvarets Forskningsinstitut (Sweden)
Saab	Saab (Sweden)
NLR	National Aerospace Laboratory (The Netherlands)
Delft University	Delft University of Technology (The Netherlands)
DLR	Deutsches Zentrum für Luft- und Raumfahrt e.V. (Germany)
EADS	European Aeronautic Defence and Space Company (Germany)
CIRA	Centro Italiano Ricerche Aerospaziali (Italy)
UNAP	University of Naples (Italy)
Leicester University	University of Leicester (United Kingdom)

The goal of the project was twofold:

- Development of analysis and unified experimental evaluation procedures which prove that a given highly augmented aircraft is sufficiently free from APC/PIO proneness.
- Establishment of a concept European Handbook and analysis tools to be used as a practical guideline during the FCS APC/PIO evaluation process.

The action group defined several challenges in order to address its research objectives:

- <u>Analysis Challenge</u>
  Development and evaluation of new mathematical analysis techniques for Category II APC/PIO assessment.
- <u>Experimental Challenge</u>
  Development and evaluation of unified flight test maneuvers that most adequately identify APC/PIO tendencies.
- <u>On-line Algorithm Challenge</u>
  Development and evaluation of mathematical algorithms that provide the most promising compensation of rate limiting effects.

During this research, emphasis was made on further understanding and development of non-linear Category II APC/PIO prediction techniques. The project provided a unique cooperation between European research establishments and industry by utilising their expertise and research simulation facilities in a coordinated approach.

3 Experimental Challenge

3.1 Simulator Campaign

For the development and assessment of new APC/PIO experimental techniques, an evaluation program was conducted as part of the GARTEUR FM(AG12) research activity. In this program, three European research simulation facilities contributed (figure 1):

- M2000-5 simulator, CEV, Istres (France)
- FENIX simulator, FOI, Stockholm (Sweden)
- National Simulation Facility NSF, NLR, Amsterdam (The Netherlands)

Nine test pilots from four different countries participated during the experiments.

The goals of the simulator campaign were:

- To establish a new database of flight test data and APC/PIO ratings to validate offline theoretical analysis results of (new) APC/PIO prediction methods
- To analyse experimental APC/PIO detection methods in order to assess the effectiveness of the newly developed tasks.

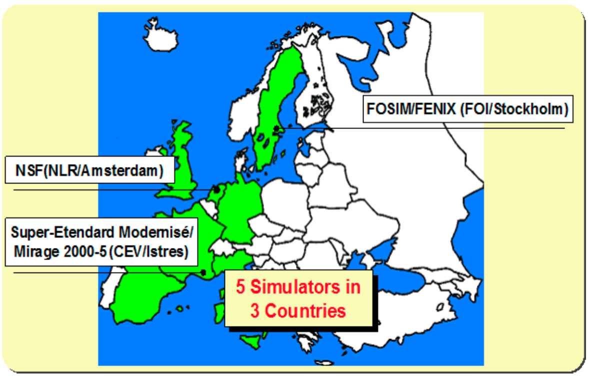


Figure 1: FM(AG12) European research simulation facilities

3.2 Simulator Configurations

<u>CEV Simulation Facility</u>

The CEV flight simulation facilities (figure 2), used during the FM(AG12) simulator evaluation campaign, consisted of:

- The Super-Etendard Modernisé cockpit, a single seat cockpit with Heads-up Display (HUD) and three windows visual system. The central stick is driven by a programmable hydraulic feel system.
- The Mirage 2000-5 cockpit, a single seat cockpit with HUD and three windows visual system.

A Thomson VISA4 visual system producing computer-generated scenes was used, including a three-channel image generator. No motion system was available.

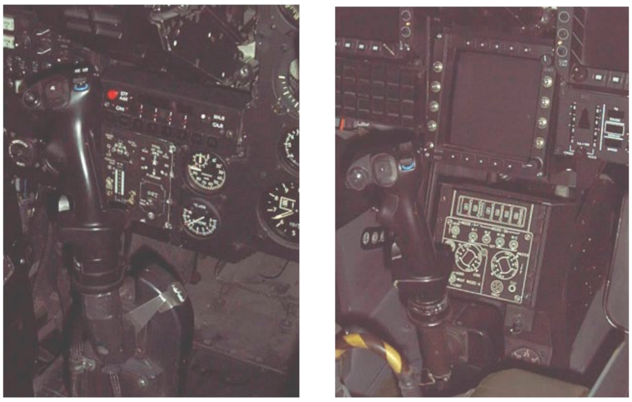


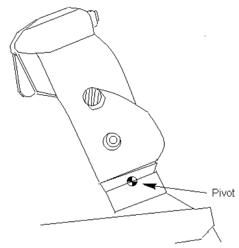
Figure 2: CEV Super-Etendard cockpit (left) and Mirage 2000-5 cockpit (right) including stick configuration

FOI Simulation Facility

The FOI research simulation facility (FENIX) is a fixed base simulator with the visual scene projected on a flat screen in front of the cockpit at a distance of 2.8 m from the pilot's eyes (figure 3). The field of view is ±30 deg sideways, 25 deg up and 20 deg down. The aircraft model is updated at 100 Hz, and the visual scene is updated at 40 to 50 Hz depending on the current computer load. The simulator's time delay, measured from a step input into the stick signal A/D converter till the visual scene actually moves is approximately 50 ms. The screen resolution is 1024x768.

Figure 3: FOI FENIX research flight simulator

The FENIX control stick used for the experiments is a prototype of the so-called LP stick that is used in the Saab JAS 39 Gripen. The stick is spring-loaded and has a very low damping. The prototype has lower damping and a slightly smaller travel in the roll direction compared to the production version. The only signal sent from the stick to the control system is stick position. In the simulator model, it was assumed that stick position is directly proportional to stick force (i.e. the stick transfer function was approximated as a pure gain). The stick forces are low compared to what is determined in MIL-F-8785C, but appropriate due to the small size of the stick. Rudder pedals were not available during the evaluation.



<u>NLR Simulation Facility</u>

The National Aerospace Laboratory NLR operates two large flight simulation facilities: the National Simulation Facility (NSF) and the Research Flight Simulator (RFS), both full motion simulators. The NSF (*figure 4*) is currently configured with an F-16 MLU cockpit and can be networked together with various desktop pilot stations in a realistic threat environment. The RFS is configured with a full-glass transport cockpit and can be linked with NLR's ATC research simulator, providing a realistic environment for the evaluation of novel ATM concepts. Depending on research requirements, the NSF and RFS can be re-configured by combining various modules.

To enable various fighters to be simulated, the cockpit can be adapted by inserting a modified center pedestal that accepts center sticks as primary pilot control. In an investigation into the handling qualities of the SAAB JAS-39 Gripen, the actual JAS-39 ministick was mounted on the generic pedestal. To obtain as much as possible the same control configurations, this stick was also utilised in the NSF for the GARTEUR FM(AG12) experiments.

Figure 4: NLR National Simulation Facility NSF

NSF technical specifications:
- Dome projection system hi-res inset (head slaved)
- MLU F-16 avionics and controls
- Multiple aircraft models
- G-cueing devices
- Six-degree-of-freedom motion system
- Targets and threats simulation

3.3 Aircraft Model and Flight Control System

The aircraft simulation model, used for the experimental challenge, was based on the ADMIRE (Aero-Data Model in Research Environment) model developed by FFA/FOI. ADMIRE is a generic model of a small single-engine fighter aircraft with a delta-canard configuration. Apart from the model, ADMIRE provides a complete simulation environment including models of the engine, FBW FCS, actuators and trimming and linearisation tools. The model was further adapted to provide level 1 handling qualities as a reference for the configurations to be evaluated during the experiments. The aircraft is augmented with a FCS in order to provide stability and sufficient handling qualities within the operational envelope (altitude <6 km, Mach < 1.2). Below Mach 0.6, the longitudinal controller provides pitch rate control. For airspeeds above Mach 0.6, it provides load factor control. An automatic speed controller provides the setting of engine thrust. A lateral controller enables to control roll and angle of sideslip. Control surface arrangements provide the control of pitch via elevons and canards while roll is controlled by elevons only. Several FCS configurations representing different levels of PIO proneness were defined for evaluation by the developed experimental APC/PIO prediction techniques. This was done by changing the maximum deflection rates of the elevons and canards. Phase compensation rate limiters were also included in the model as defined by Saab and DASA (currently EADS).

3.4 Flight Test Preparation

For the experimental evaluations, baseline FCS configurations were defined providing a gradual increase of APC/PIO proneness. The aim was to have several references available in order to compare the effectiveness of the different APC/PIO experimental evaluation techniques. For the FCS adaptation, three (phase compensated) rate limiters were included based on the standard MATLAB™ rate limiter, and phase compensated rate limiters based on Saab and DASA (EADS) designs. Maximum deflection rates of the elevons and canards were defined in order to obtain an expected behavior of the FCS ranging from ‘good’ to ‘really bad’. The ‘good’ configurations were mainly intended as a reference for the pilot and for comparison with the other configurations during flight test analysis. (*Table 2*). The configurations were evaluated in two flight conditions throughout the experiment (Mach 0.25; Altitude 500m / Mach 0.8; Altitude 5000m).

The newly developed experimental techniques were compared with current APC/PIO standard evaluation and demonstration maneuvers. In this process, a difference was made between heads-up display tracking tasks and non-display tracking tasks (evaluation maneuvers).

Table 2: FCS configurations for evaluation of APC/PIO experimental techniques

Rates canard / elevons [deg/sec]						expected behaviour	No.
flight condition			flight condition				
DASA	Matlab	SAAB	DASA	Matlab	SAAB		
50/150	∞/∞	50/150	15/45	∞/∞	15/45	good	1
40/120	40/120	40/120	10/30	10/30	10/30	medium	2
30/90	30/90	30/90	7/21	7/21	7/21	bad	3
20/60	20/60	20/60	5/15	5/15	5/15	really bad	4

<u>Display Tracking Tasks</u>

The display tracking tasks were developed during the project to investigate unified experimental techniques for APC/PIO assessment. The aim was to define evaluation tasks that include the characteristic conditions necessary to generate a possible PIO. As such, the requirements for the design of these tasks were:

- Simulation of high gain situations
- Ensuring rate limiter activation
- Unpredictable
- Adequate duration of the task
- Independent from aircraft
- Increasing demands

The tasks, as evaluated during the simulator campaign, were developed by DLR based on ten proposal tasks. Simulator tests were conducted at FOI, using DLR questionnaires, to select a candidate task for further evaluation.

The HUD tracking tasks consisted of tasks for pitch (*figure 5*) and roll (*figure 6*) and combined pitch and roll. The tasks were evaluated with the different FCS configuration in a varying order. The test pilot was briefed to track the task as aggressively as possible during the run after which the pilot gave a PIO rating. A total of about 48 runs were conducted using the HUD tracking tasks with each run lasting about one minute.

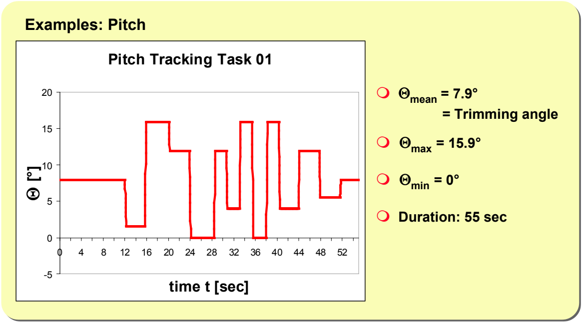


Figure 5: FM(AG12) HUD pitch tracking task

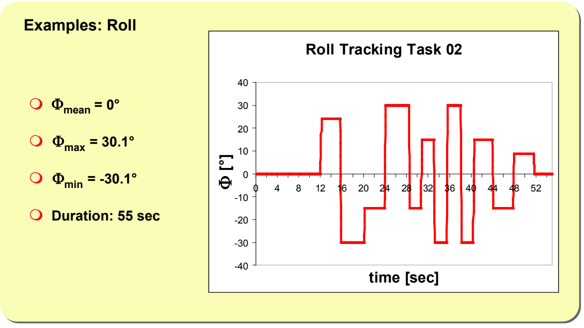


Figure 6: FM(AG12) HUD roll tracking task

The tracking tasks were presented on the aircraft's HUD (*figure 7*). A moving bar in the HUD represents the task. Two bars above and below it are the limits for 'adequate performance' that should only give some assistance for answering the questions in the PIO rating scale. These limits must also not be deemed as an area where the performance is sufficient. The task of the pilot is to concentrate on the middle bar and to compensate any tracking error. An adequate time limit to capture the commanded step input is indicated by blinking of the adequate bars 1.8 seconds after the input command.

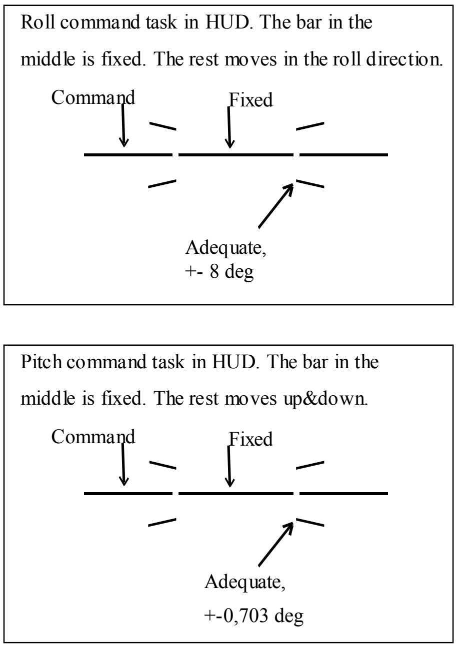


Figure 7: Presentation of developed APC/PIO tracking tasks in the HUD

Evaluation Maneuvers

Standard Evaluation Maneuvers (STEM)[6] and Demonstration Maneuvers (DM)[7] were selected for comparison with the developed APC/PIO tracking tasks. The maneuvers were flown after the tracking tasks and for those cases that exposed a potential APC/PIO problem. Comparison of both the performance of the HUD tracking task and evaluation maneuver may then indicate the effectiveness of the task or maneuver to most adequately predict a PIO prone configuration. In total, about 10 runs for the maneuvers were performed. The following maneuvers were selected for evaluation and adapted based on the capabilities of the available simulator facilities:

- Pitch Attitude Capture and Hold (DM 21)
- Roll Attitude Capture and Hold (DM 22)
- Offset Approach to Landing (NLR/STEM 20)
- Sharkenhausen (STEM 11)
- Target Tail Chase (CEV)
- Carrier Landing (CEV)

The Pitch Attitude Capture and Hold maneuver was modified at the FOI simulation facility (figure 8). A small cross representing the aircraft's x-axis is fixed on the HUD. At the start of the run, the horizontal lines are positioned 5 deg above and 10 deg below the cross. The horizontal lines always move together with the HUD's artificial horizon, so that moving the cross from the gap in one line to the other corresponds to a 15 deg pitch attitude change. No adequate limits are drawn, so the pilot has to use the standard attitude scale to determine whether the attitude is within ±2 deg of the required attitude or not.

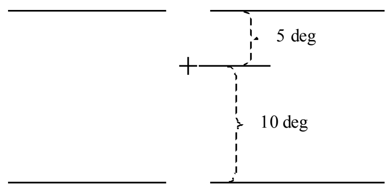


Figure 8: FOI Pitch Attitude Capture and Hold symbology

The *Pitch Attitude Capture and Hold* maneuver was also adapted for the NLR NSF configuration (*figure 9*). Main objective of the maneuver was evaluation of PIO proneness of the various flight control configurations at the pilot's discretion using a pitch reference as a guide. The maneuver consisted of an aggressive 5 deg pitch angle capture with a modified HUD tracking task display. The aim was to let the pilot have some room for free experimentation to assess APC/PIO proneness. The pilot was briefed to assign a PIO rating when he felt confident enough.

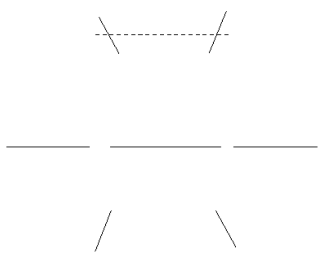


Figure 9: NLR Pitch Attitude Capture and Hold symbology

The *Roll Attitude Capture and Hold* maneuver was adapted for the FOI experiments (*figure 10*). A horizontal line is the HUD's artificial horizon. The middle of the cross is always in the middle of the gap in the artificial horizon. Aligning the cross with the artificial horizon corresponds to a ± 45 deg bank angle. The short horizontal lines represent the adequate limits of ±4 deg.

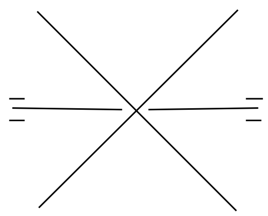


Figure 10: FOI Roll Attitude Capture and Hold symbology

The NLR *Roll Attitude Capture and Hold* maneuver, (*figure 11*) provided evaluation of APC/PIO proneness of the various flight control configurations at the pilot's discretion using a roll reference as a guide. The maneuver consisted of a 45 deg bank angle capture with a modified HUD tracking task display. Again, the aim was to provide the pilot with some freedom for experimentation to assess APC/PIO proneness. The pilot was briefed to perform the maneuver as aggressively as possible and to assign a PIO rating when he felt confident enough.

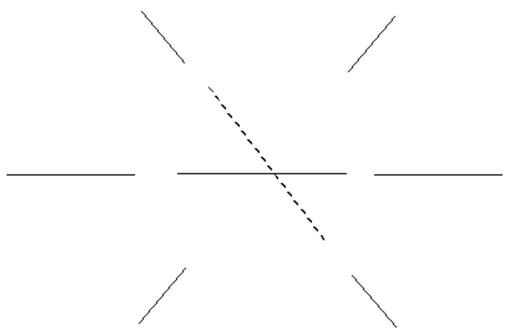


Figure 11: NLR Roll Attitude Capture and Hold symbology

The *Offset Approach to Landing* maneuver, as implemented on the NLR NSF, was initially developed during an earlier investigation into the handling qualities of the SAAB JAS-39 Gripen (*figure 12*). The objectives of the maneuver were to evaluate PIO proneness of the various flight control configurations in a challenging landing environment based on S-turns on final and moderate turbulence.
The maneuver consists of:

- Overflying the top of poles at 4500 and 1500 m (as if the pilot were landing on them). Passing the 4500 m pole the pilot would fly to the opposite 1500 m pole by crossing the runway centerline (S-turn). Upon crossing the 1500 m pole he would immediately maintain runway heading in an offset position. Runway alignment would occur after passing the 618 m pole.

- Adequate performance was defined by landing preferably ‘on the numbers’. An imaginary ‘box’ around the landing zone was defined for the adequate performance limit.
- Approach and landing speed was aimed at 150 knots.

The pilot was briefed to do his best to actually land the aircraft, even if he would go around in real life. The simulation was ended well before full stop.

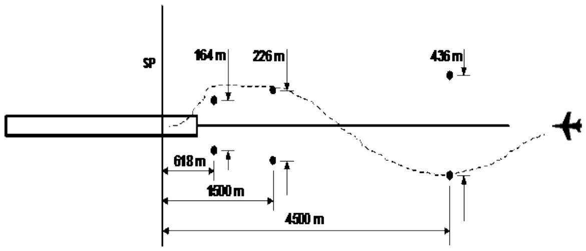


Figure 12: NLR Offset Approach to Landing maneuver

The *Sharkenhausen* maneuver (*figure 13, HUD view*), as evaluated at FOI, starts with a target that begins co-speed with the test aircraft and with a 180° heading difference. The target aircraft begins 5000 ft abreast and 5000 ft higher than the test aircraft. During the maneuver, the target aircraft maintains straight and level flight at constant airspeed. When the target reaches a position 1.3 nm downrange, the pilot should aggressively acquire and track the target. The target should be captured in an 80 mil reticle for 2 seconds. For the FOI facility, the turn towards the target was initiated earlier than specified, at approximately 1.7 nm instead of 1.3 nm, in order to keep the target aircraft within the simulator’s field of view. A small cross that is fixed on the HUD is used as pipper. As the target aircraft is too distant to be visible when the run begins, a line is used to point it out, and a square is drawn at the position of the target aircraft. The circle around the cross shows the limit for adequate target tracking. The diameter of the circle is 80 milliradians in the pilot’s field of view.

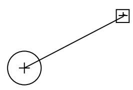


Figure 13: FOI Sharkenhausen symbology

The objective of the CEV *Target Tail Chase* maneuver (*figure 14*) is to check the ability to acquire and track a target. The target and the test aircraft are trimmed at Mach 0.8 and at an altitude of 5000 m and with the same heading. The task starts with the test aircraft at 500 m slant range position relative to the target, offset 10 deg in lateral (right) and in longitudinal (down). When the evaluation pilot starts to roll to the right, the target initiates a 3g level turn to the left and after its heading has changed 180 deg, it executes a roll reversal to turn right.

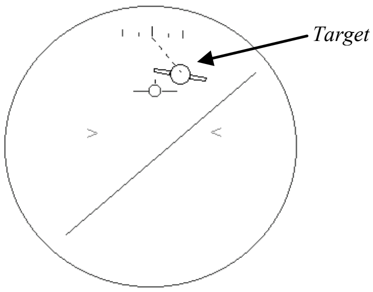


Figure 14: CEV Target Tail Chase symbology

The CEV *Carrier Landing* maneuver (*figure 15*) was implemented to check the ability to perform HUD precision landings on a moving platform, of which the axis of the runway has an offset of 8 deg. The evaluation of the task starts 15 seconds before touchdown. During the task, the aircraft vertical speed and angle-of-attack have to be kept constant. The pilot has to align the 3.5 deg glide slope reference reticle on the base of a triangular aiming marker painted on the fore end of the runway.

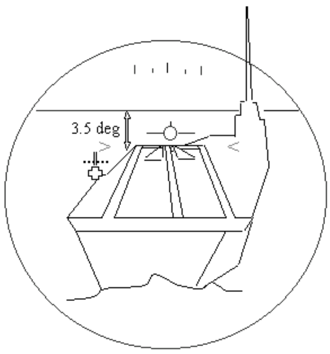


Figure 15: CEV Carrier Landing symbology

APC/PIO Rating Scale

A new APC/PIO rating scale (*figure 16*) was developed for the evaluation of the APC/PIO experimental techniques. The design of the scale, performed by Dipl.-Ing. Hans Mehl of DLR, was based on the collection of experience of project partners, experiences in literature and collaboration with pilots. The scale is made up of six point ratings with no half point ratings. The pilot assesses APC/PIO proneness via a decision tree that includes a description of the pilot perception of the aircraft behavior. The scale is specially designed to take into account safety, task achievement and performance. Guidelines support the rating scale for practical use.

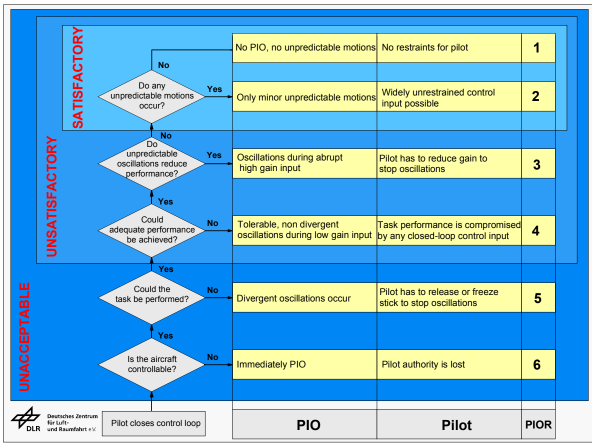


Figure 16: FM(AG12) new APC/PIO rating scale

4 Summary of Experimental Results

The experimental results were analysed by means of a qualitative assessment of the experimental APC/PIO detection methods as evaluated in the simulator. For this analysis, the effectiveness of the developed HUD tracking tasks to detect a potential PIO problem was compared to the Standard Evaluation and Demonstration Maneuvers (STEM/DM) as selected for each facility. For the assessment of the evaluated experimental methods, the mean value of the PIO ratings of all pilots for the same task and condition was calculated. In addition, the standard deviation, or root mean square (RMS), was calculated to provide an indication on the scatter of the data and effectiveness of the evaluated method. It should be emphasised that, strictly speaking, it is not correct to calculate the mean value of the numeric handling qualities or PIO ratings. This is because these rating scales are essentially non-interval scales. Nevertheless, this was not taken into account for the analysis assuming the calculated results would be more or less representative. If the other pilots rate the system significantly better (e.g. PIOR 3) while one pilot experiences a control loss and departure (rating 6) then, despite the low mean rating, there still may exist a potential safety problem. As such, the maximum rating for all pilots in the same condition was also determined. The data of mean PIO ratings and RMS values were used for the analysis to reveal certain tendencies of the task or maneuver to most effectively predict a PIO configuration. For the maneuver analysis, the emphasis has been on the quality of the experimental methods for prediction of PIO proneness and not on the quality of the aircraft/control system.

4.1 CEV Experimental Results

Analysis of the experimental results at the CEV simulator facility, regarding the APC/PIO detection maneuvers, indicated that:

- The developed HUD tracking tasks proved to be more effective than the target tail chase and carrier landing maneuvers.
- Experience shows that pilots tend to reduce their gain following a run with severe APC/PIO. Additionally, it may be good practice to increase the randomness of the simulator runs.

4.2 FOI Experimental Results

For the FOI experiments, STEM 11 (Sharkenhausen) and DM 21 (Pitch Attitude Capture and Hold) and DM 22 (Bank Angle Capture and Hold) were selected and modified for comparison with the HUD tracking tasks. APC/PIO ratings given by each pilot from the STEM and DMs were compared with the ratings obtained from the corresponding tracking tasks. STEM 11 was compared to the combined pitch and roll task, DM 21 was compared to the pitch HUD tracking task and DM 22 was compared to the roll HUD tracking. Results of the analysis are indicated in Table 3.

Table 3: APC/PIO rating differences between FOI HUD tracking tasks and maneuvers (m3, m4 and m5)

m3, Sharkenhausen.	36		comparisons made between maneuver and combined axes HUD tracking task
	30	83%	comparisons with PIOR difference 1 or less
	33	92%	comparisons with PIOR difference 2 or less
m4, Pitch attitude capture and hold.	43		comparisons made between maneuver and pitch HUD tracking task
	37	86%	comparisons with PIOR difference 1 or less
	41	95%	comparisons with PIOR difference 2 or less
m5, Roll angle capture and hold.	42		comparisons made between maneuver and roll HUD tracking task
	30	71%	comparisons with PIOR difference 1 or less
	36	86%	comparisons with PIOR difference 2 or less

The results appear to indicate a generally good agreement between the HUD tracking tasks and evaluation maneuvers. In 80% of the cases, the difference in ratings given by the same pilot was 1 or less, and in 91% of the cases it was 2 or less. Further analysis of the flight test data revealed that:

- Attitude capture maneuvers proved to be more effective than the corresponding HUD tasks. This was probably caused by smaller amplitude of the HUD tasks.
- For the combined axes, the HUD task was better. The Sharkenhausen proved to be less useful and failed to expose some undesirable characteristics.

4.3 NLR Experimental Results

For the NSF APC/PIO evaluation methods assessment, DM 21 was compared to the HUD pitch task, DM 22 compared to the HUD roll task and STEM 20 compared to the HUD combined (pitch+roll) task. The NSF evaluation maneuvers were adapted and implemented as described earlier.

Assessment of the individual ratings given for the HUD tracking tasks compared to the maneuvers obtained the results (task repetition included) as presented in Table 4.

Table 4: APC/PIO rating differences between NLR HUD tracking tasks and maneuvers

Tasks	PIOR difference <=1	PIOR difference <=2	No. of comparisons
HUD pitch vs. DM21	84%	100%	25
HUD pitch vs. DM21 repetition	72%	100%	25
HUD roll vs. DM22	89%	89%	19
HUD roll vs. DM22 repetition	84%	95%	19
HUD pitch+roll vs. STEM20	50%	70%	20

The results again indicate a good agreement between the HUD tasks and evaluation maneuvers. In approximately 75 % of the cases (69% including repetitions) the PIO rating difference was equal or less than 1. In about 86% of the cases (88% including repetitions) the PIO rating was 2 or less. It can be seen that the offset approach to landing maneuver did not perform well in this respect. Furthermore, it was found that:

- Pilot ratings were given consistently for both initial task performance and repetition.
- Pitch attitude capture task seems more effective than the corresponding HUD task.
- HUD roll task seems more effective than the bank angle capture task.
- For combined axes, the HUD task seems more effective than the NSF offset approach to landing task. It was determined that the most probable cause for this was a lack of sufficient high gain elements within the offset landing setup. Including, for instance, additional airspeed and altitude restrictions may have provided a more demanding (high gain) task.

5 Conclusions & Future research

To address the need for the development of practical design guidelines on APC/PIO analysis and experimental evaluation techniques, an Action Group on Aircraft Pilot Coupling (FM(AG12)) was recently established within the framework of the European GARTEUR organisation. The action group, addressing several research challenges on APC/PIO analysis, experimental and on-line detection methods, achieved a promising progress into the prediction and further understanding of APC/PIO, in particular for the higher order Category II/III PIO phenomena. The experimental challenge, as described in this paper, was defined as part of the project in order to investigate new experimental techniques for APC/PIO susceptibility assessment. The preliminary results of the simulator campaign that was conducted indicates that:

- The new APC/PIO experimental techniques appear to be generally in good agreement with the standard evaluation maneuvers.
- Initial results indicate, however, that the new experimental techniques for the combined axes may be the most promising.
- Further development of experimental methods may be focussed on multi-axes acquisition and tracking maneuvers to predict APC/PIO proneness effectively.

Future research in the area of APC/PIO may build further on the most promising results of the GARTEUR action group in order to address the more complex types of Category II and III PIO and non-oscillatory PIO events. Essential within this process is to maintain a co-ordinated approach that combines the further maturing of the promising PIO prediction methods with experiments. The improved theoretical analysis methods should be correlated against experimental data to assess their validity. The established database within FM(AG12) may be utilised for this purpose and extended if necessary.

Predictive evaluation techniques and tasks for Category II/III and non-oscillatory PIO assessment may be refined further while the validation of simulator test results with actual in-flight tests may be considered.

Continuation of the GARTEUR Action Group on Aircraft Pilot Coupling, as is currently foreseen, will further mature the most promising PIO prediction techniques and contribute towards a practical guideline for a consistent aircraft pilot coupling elimination process.

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