GARTEUR Open

EVALUATION OF PROMINENT PIO SUSCEPTIBILITY CRITERIA

by

GARTEUR Action Group FM(AG12)

This report has been published under auspices of
the Flight Mechanics Group of Responsables
of the Group for Aeronautical Research and
Technology in EURope (GARTEUR)
### List of Authors

<table>
<thead>
<tr>
<th>Author</th>
<th>Institution</th>
<th>Contribution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hafid Smaïli</td>
<td>NLR</td>
<td>Chapter 1, 5, contribution to chapter 2, 3 and editor</td>
</tr>
<tr>
<td>Stefano Scala</td>
<td>CIRA</td>
<td>Contribution to chapter 2 and 3</td>
</tr>
<tr>
<td>F. Amato</td>
<td>UNAP</td>
<td>Contribution to chapter 3</td>
</tr>
<tr>
<td>Rogier van der Weerd</td>
<td>DUT</td>
<td>Contribution to chapter 3</td>
</tr>
<tr>
<td>Gunnar Hovmark</td>
<td>FFA</td>
<td>Contribution to chapter 4</td>
</tr>
<tr>
<td>Hans-Joachim Mehl</td>
<td>DLR</td>
<td>Contribution to chapter 4</td>
</tr>
<tr>
<td>Hans-Christoph Oelker</td>
<td>DASA</td>
<td>DASA industrial view</td>
</tr>
<tr>
<td>Lars Rundqwist</td>
<td>SAAB</td>
<td>SAAB industrial view</td>
</tr>
</tbody>
</table>
Summary

This report ‘Evaluation of Prominent PIO Susceptibility Criteria’ presents a literature survey on current criteria for the prediction of pilot-in-the-loop oscillations. The document is a deliverable of Workpackage 1 (task 1.1) ‘Analysis Challenge’ of GARTEUR action group FM(AG12) ‘Pilot-in-the-Loop Oscillations; Analysis and Test Techniques for their Prevention’.

The document provides a description of criteria for the prediction of category I and II PIOs. The theoretical backgrounds of the criteria are described including their effectiveness to predict PIOs in the aforementioned categories. The goal of the report is to provide the analysis teams in the project a consolidated view on the applicability of the most prominent set of PIO susceptibility criteria. The selected criteria in this report will be used by the design teams to develop analysis and evaluation techniques, which prove that a given highly augmented aircraft is sufficiently free from PIO proneness. In this process, priority will be given to the development of prediction procedures for Category II PIOs. Analysis methods for PIO susceptibility assessment will be addressed separately by the design teams.

The results in this report indicate that the Category I and II prominent PIO criteria have a high degree of success in predicting PIOs for the cases evaluated. However, the Category II criteria, although promising in predicting PIO, should be developed further.

This report was established with contributions from CIRA, UNAP, INTA, FFA, DLR and NLR. Part of the material in this report has been provided by AGARD/RTO Working Group 23 on Flight Control. Integration and final editing of the supported material was performed by NLR.
Contents

List of Authors i
Summary ii
List of Figures v
List of Tables vii
List of Symbols and Abbreviations viii
Distribution List xi

1. Introduction 1

2. Aircraft-Pilot Coupling and Pilot-in-the-Loop Oscillations 3
   2.1 General 3
   2.2 Pilot-in-the-Loop Oscillations (PIO); Background and Classifications 3
   2.3 Prominent PIO prediction criteria 5
      2.3.1 Category I PIO Criteria 7
      2.3.2 Category II PIO Criteria 7
      2.3.3 Criterion Evaluation 8

3. Category I PIO Criteria Evaluation 11
   3.1 General 11
   3.2 Neal-Smith Criterion 11
      3.2.1 Criterion Background 11
      3.2.2 Criterion Evaluation 12
   3.3 Bandwidth / Phase Delay Criterion 13
      3.3.1 Criterion Background 13
      3.3.2 Criterion Evaluation 14
   3.4 Smith-Geddes Criterion 15
      3.4.1 Criterion Background 15
      3.4.2 Criterion Evaluation 16
   3.5 Phase Rate Criterion and Gain Phase Template (Average Phase Rate) 17
      3.5.1 Criterion Background 17
      3.5.2 Criterion Evaluation 18
   3.6 Gibson Time Domain Dropback 22
      3.6.1 Criterion Background 22
      3.6.2 Criterion Evaluation 25
   3.7 Discussion of Category I PIO Criteria 27
      3.7.1 Criterion Effectiveness 27
      3.7.2 Criterion Gaps and Extensions 29
4. Category II PIO Criteria Evaluation
   4.1 General
   4.2 Time Domain Neal-Smith Criterion
      4.2.1 Criterion Background
      4.2.2 Criterion Evaluation
   4.3 Open Loop Onset Point Criterion (OLOP)
      4.3.1 Criterion Background
      4.3.2 Criterion Evaluation

5. Conclusions

Industrial View

References
List of Figures

Figure 1: Application of the Neal-Smith criterion to the landing databases LAHOS, HAVE PIO, HAVE CONTROL ................................................................. 12
Figure 2: Application of the bandwidth/phase delay criterion to the landing databases LAHOS, HAVE PIO, HAVE CONTROL .......................................................... 14
Figure 3: Application of the Smith-Geddes criterion to the landing databases LAHOS, HAVE PIO, HAVE CONTROL ................................................................. 16
Figure 4: Application of the phase rate criterion to the landing databases LAHOS, HAVE PIO, HAVE CONTROL ................................................................. 18
Figure 5: The gain phase template part of the Average Phase Rate criterion, with the evaluation of configuration LAHOS 5_1 ............................................................ 19
Figure 6: Evaluation of the LAHOS configuration 5_1 by the Gibson gain-phase template. ... 21
Figure 7: Pitch axis step response characteristics for application of time domain dropback criterion ............................................................................... 23
Figure 8: Original dropback criterion boundaries................................................................. 23
Figure 9: Frequency-domain definition of dropback using the frequency response of pitch rate to control inceptor force q/F_{e}(s) ................................................................. 24
Figure 10: Generic step responses showing the relationship between pitch attitude and flight path angle ............................................................................... 25
Figure 11: Application of Gibson Dropback criterion to the landing databases LAHOS, HAVE PIO, HAVE CONTROL ................................................................. 25
Figure 12: Application of the modified dropback criterion to the landing databases LAHOS, HAVE PIO, HAVE CONTROL ................................................................. 26
Figure 13: The closed-loop tracking task ............................................................................... 31
Figure 14: A typical Simulink system for use of the criterion ............................................... 33
Figure 15: A typical time history, for the Neal-Smith configuration 1c. ............................... 34
Figure 16: Level 1, 2 and 3 HQ limits from ref. [45] .............................................................. 34
Figure 17: Constraints for \( \text{rms} \theta_c \) at the smallest feasible D vs. D, \( \theta_c = 5^\circ \) ....... 36
Figure 18: Constraints for minimum \( \frac{\partial \text{rms} \theta_c}{\partial D} \) vs. D, \( \theta_c = 5^\circ \) ................. 36
Figure 19: Constraints for maximum \( \frac{\partial^2 \text{rms} \theta_c}{\partial D^2} \) vs. D, \( \theta_c = 5^\circ \) ....................... 37
Figure 20: Constraints for \( \text{rms} \theta_c \) at the smallest feasible D vs. D, \( \theta_c = 2.5^\circ \) .......... 37
Figure 21: Constraints for \( \text{rms} \theta_c \) at the smallest feasible D vs. D, \( \theta_c = 10^\circ \) ............. 38
Figure 22: 565 deg/s rate limit ............................................................................................. 39
Figure 23: 35 deg/s rate limit ............................................................................................. 40
Figure 24: 15 deg/s rate limit ............................................................................................. 41
Figure 25: Jump phenomenon after rate limiting onset............................................................. 43
Figure 26: Physical significance of the OLOP parameter.......................................................... 44
Figure 27: Validation of the OLOP criterion using the FOSIM data.......................................... 46
List of Tables

Table 1: Evaluation of PIO prediction ................................................................. 8
Table 2: Landing databases for assessment of PIO criteria .................................. 9
Table 3: PIO prediction with the Neal-Smith criterion ........................................ 13
Table 4: PIO prediction with the Bandwidth-Phase Delay criterion ..................... 15
Table 5: PIO prediction with the Smith-Geddes criterion .................................... 16
Table 6: PIO prediction with Average Phase Rate plus gain-phase template criterion 20
Table 7: PIO prediction with Gibson gain-phase template .................................. 21
Table 8: PIO prediction with Gibson dropback criterion .................................... 26
Table 9: PIO prediction with modified dropback criterion .................................. 27
Table 10: Performance Indices of Category I PIO prediction criteria .................... 28
Table 11: Lateral databases for PIO research ..................................................... 45
# List of Symbols and Abbreviations

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>ADMIRE</td>
<td>Aero-Data Model in Research Environment</td>
</tr>
<tr>
<td>EREA</td>
<td>Association of European Research Establishments in Aeronautics</td>
</tr>
<tr>
<td>AG</td>
<td>Action Group</td>
</tr>
<tr>
<td>APC</td>
<td>Aircraft-Pilot Coupling</td>
</tr>
<tr>
<td>APR</td>
<td>Average Phase Rate</td>
</tr>
<tr>
<td>ARE</td>
<td>Algebraic Riccati Equation</td>
</tr>
<tr>
<td>CEV</td>
<td>Centre d'Essais en Vol</td>
</tr>
<tr>
<td>CIRA</td>
<td>Centro Italiano Ricerche Aerospaziali</td>
</tr>
<tr>
<td>DAv</td>
<td>Dassault Aviation</td>
</tr>
<tr>
<td>DASA</td>
<td>DaimlerChrysler Aerospace</td>
</tr>
<tr>
<td>DE</td>
<td>Germany</td>
</tr>
<tr>
<td>DERA</td>
<td>Defence Evaluation and Research Agency</td>
</tr>
<tr>
<td>DLR</td>
<td>Deutsches Zentrum für Luft-und Raumfahrt e.V.</td>
</tr>
<tr>
<td>DUT</td>
<td>Delft University of Technology</td>
</tr>
<tr>
<td>EG</td>
<td>Exploratory Group</td>
</tr>
<tr>
<td>ES</td>
<td>Spain</td>
</tr>
<tr>
<td>FCS</td>
<td>Flight Control System</td>
</tr>
<tr>
<td>FFA</td>
<td>Flygtekniska Försöksanstalten (The Aeronautical Research Institute of Sweden)</td>
</tr>
<tr>
<td>FM/GoR</td>
<td>Flight Mechanics Group of Responsables</td>
</tr>
<tr>
<td>FOSIM</td>
<td>Forskningssimulator</td>
</tr>
<tr>
<td>FR</td>
<td>France</td>
</tr>
<tr>
<td>GARTEUR</td>
<td>Group for Aeronautical Research and Technology in EURope</td>
</tr>
<tr>
<td>INTA</td>
<td>Instituto Nacional de Técnica Aeroespacial</td>
</tr>
<tr>
<td>IT</td>
<td>Italy</td>
</tr>
<tr>
<td>LAAS</td>
<td>Laboratoire d’Analyse et d’Architecture des Systèmes</td>
</tr>
<tr>
<td>LMI</td>
<td>Linear Matrix Inequalities</td>
</tr>
<tr>
<td>NL</td>
<td>The Netherlands</td>
</tr>
<tr>
<td>NLR</td>
<td>Nationaal Luchtvaart- en Ruimtevaartlaboratorium</td>
</tr>
<tr>
<td>NSF</td>
<td>National Simulation Facility</td>
</tr>
<tr>
<td>OLOP</td>
<td>Open Loop Onset Point</td>
</tr>
<tr>
<td>ONERA</td>
<td>Office National d’Études et de Recherches Aéropatiales</td>
</tr>
<tr>
<td>PIO</td>
<td>Pilot-Involved (or Pilot-Induced / Pilot-in-the-Loop) Oscillations</td>
</tr>
<tr>
<td>PVS</td>
<td>Pilot-Vehicle System</td>
</tr>
<tr>
<td>SAAB</td>
<td>Saab AB</td>
</tr>
<tr>
<td>SE</td>
<td>Sweden</td>
</tr>
<tr>
<td>SUE</td>
<td>Super-Etendard Simulator</td>
</tr>
<tr>
<td>Acronym</td>
<td>Description</td>
</tr>
<tr>
<td>--------</td>
<td>-------------------------------------------------</td>
</tr>
<tr>
<td>TBC</td>
<td>To Be Confirmed</td>
</tr>
<tr>
<td>TBD</td>
<td>To Be Defined</td>
</tr>
<tr>
<td>UNAP</td>
<td>Università degli Studi di Napoli Federico II</td>
</tr>
<tr>
<td>WP</td>
<td>Work Package</td>
</tr>
<tr>
<td>XC</td>
<td>GARTEUR Executive Committee</td>
</tr>
</tbody>
</table>
### Distribution List

(Distribution is via e-mail and Wide Area Network if not otherwise specified)

#### GARTEUR Executive Committee (hardcopy)

<table>
<thead>
<tr>
<th>Name</th>
<th>Country</th>
<th>Organization</th>
</tr>
</thead>
<tbody>
<tr>
<td>F. Abbink</td>
<td>NL</td>
<td>NLR</td>
</tr>
<tr>
<td>P. Garcia Samitier</td>
<td>ES</td>
<td>INTA</td>
</tr>
<tr>
<td>A. Gustafsson</td>
<td>SE</td>
<td>FFA</td>
</tr>
<tr>
<td>D.E. Mowbray – Chairman XC</td>
<td>UK</td>
<td>DERA</td>
</tr>
<tr>
<td>D. Nouailhas</td>
<td>FR</td>
<td>ONERA</td>
</tr>
<tr>
<td>H.J. Schepers</td>
<td>DE</td>
<td>DLR</td>
</tr>
</tbody>
</table>

#### GARTEUR Secretary (hardcopy)

<table>
<thead>
<tr>
<th>Name</th>
<th>Country</th>
</tr>
</thead>
<tbody>
<tr>
<td>O.K. Sodha</td>
<td>UK</td>
</tr>
<tr>
<td></td>
<td>DERA</td>
</tr>
</tbody>
</table>

#### GARTEUR Flight Mechanics Group of Responsables (hardcopy)

<table>
<thead>
<tr>
<th>Name</th>
<th>Country</th>
<th>Organization</th>
</tr>
</thead>
<tbody>
<tr>
<td>B. Brännström</td>
<td>SE</td>
<td>FMV</td>
</tr>
<tr>
<td>P. Caap</td>
<td>SE</td>
<td>FFA</td>
</tr>
<tr>
<td>J. Hall</td>
<td>UK</td>
<td>DERA</td>
</tr>
<tr>
<td>H.T. Huynh – Monitoring Responsable FM(AG12)</td>
<td>FR</td>
<td>ONERA</td>
</tr>
<tr>
<td>P.G.A.M. Jorna</td>
<td>NL</td>
<td>NLR</td>
</tr>
<tr>
<td>A. Kröger</td>
<td>DE</td>
<td>DASA</td>
</tr>
<tr>
<td>F. Muñoz – Chairman FM-GoR</td>
<td>ES</td>
<td>INTA</td>
</tr>
<tr>
<td>R. Rodloff</td>
<td>DE</td>
<td>DLR</td>
</tr>
</tbody>
</table>

#### GARTEUR Flight Mechanics Industrial Points of Contact (hardcopy)

<table>
<thead>
<tr>
<th>Name</th>
<th>Country</th>
</tr>
</thead>
<tbody>
<tr>
<td>J. Choplin</td>
<td>FR</td>
</tr>
<tr>
<td>E. Kullberg</td>
<td>SE</td>
</tr>
<tr>
<td></td>
<td>SAAB</td>
</tr>
</tbody>
</table>

#### GARTEUR FM(AG12) Participants

<table>
<thead>
<tr>
<th>Name</th>
<th>Country</th>
<th>Organization</th>
</tr>
</thead>
<tbody>
<tr>
<td>F. Amato</td>
<td>IT</td>
<td>UNAP</td>
</tr>
<tr>
<td>S. Bennani</td>
<td>NL</td>
<td>DUT</td>
</tr>
<tr>
<td>J.M. Biannic</td>
<td>FR</td>
<td>ONERA</td>
</tr>
<tr>
<td>J. Choplin</td>
<td>FR</td>
<td>DAv</td>
</tr>
<tr>
<td>M. Crouzet</td>
<td>FR</td>
<td>CEV</td>
</tr>
<tr>
<td>B. Dang-Vu – Chairman FM(AG12)</td>
<td>FR</td>
<td>ONERA</td>
</tr>
<tr>
<td>G. Duus – Vice-Chairman FM(AG12)</td>
<td>DE</td>
<td>DLR</td>
</tr>
<tr>
<td>B. Escande</td>
<td>FR</td>
<td>ONERA</td>
</tr>
</tbody>
</table>
M. Garcia (FR) LAAS
G. Hovmark (SE) FFA
R. Iervolino (IT) UNAP
A. Knoll (DE) DASA
H.J. Mehl (DE) DLR
T. Norén (SE) FFA
H.-Chr. Oelker (DE) DASA
C. Pittet (FR) LAAS
I. Queinnec (FR) LAAS
L. Rundqwist (SE) SAAB
S. Scala (IT) CIRA
M.H. Smaïli (NL) NLR
S. Tarbouriech (FR) LAAS
P. Vicente (ES) INTA
R. van der Weerd (NL) DUT
T. Wilmes (DE) DLR

Others
M. Bauschat (DE) DLR
L. Forssell (SE) FFA
F. Johansson (SE) FFA
F. Karlsson (SE) SAAB
R. Luckner (DE) DASA
J.F. Magni (FR) ONERA
M. Selier (NL) NLR
R. van der Sluis (NL) DUT
A. Varga (DE) DLR
C. Vidal (IT) CIRA
1. Introduction

The development of fly-by-wire flight control systems for modern aircraft initiated an increase in 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. 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 behaviour. 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 unable to adapt himself.

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 PIO. Although most established PIO criteria were determined to be suitable for the prediction of linear PIOS, a set of criteria to evaluate non-linear PIO phenomena is still under investigation and are not yet adequate enough. In addition, current industry standards lack a specific guideline providing unified PIO test techniques and analysis tools for aircraft design.

The GARTEUR action group FM(AG12) ‘Pilot-in-the-Loop Oscillations; Analysis and Test Techniques for their Prevention’ addresses the need for the development of a guideline on PIO testing and analysis. The goal of the project is the development of analysis and test procedures which prove that a given highly augmented aircraft is sufficiently free from PIO proneness. In this process, an emphasis is made on the development of Category II PIO prediction procedures.

As part of the project’s objectives, design teams will work on the application of existing and new mathematical analysis tools, thereby comparing their capability to predict whether or not a given pilot-vehicle system is PIO prone. This report provides the analysis teams a consolidated view on the applicability of the most prominent set of Category I and II PIO susceptibility criteria. After a brief description on the background and characteristics of PIO and APC in chapter 2, the most prominent criteria for Category I and II PIO susceptibility assessment are described (chapter 3 and 4). Following a description on its theoretical background, each criterion will be evaluated on its effectiveness to predict the relevant PIO category. The applicability of the prominent criteria will be summarised in chapter 5.
Part of the material in this report has been provided by AGARD/RTO Working Group 23 on Flight Control, which edited a report on best practices in flight control design. A selection of reference material is provided in the literature list at the end of this report.
2. Aircraft-Pilot Coupling and Pilot-in-the-Loop Oscillations

2.1 General

This part presents an introduction to Aircraft-Pilot Coupling (APC) or Pilot-in-the-Loop Oscillations (PIO). The description will start with the background on the PIO phenomenon and the classifications that categorize PIO (2.2). Following this, a selection of criteria will be made that are the most prominent for assessing Category I and II PIOs (2.3).

2.2 Pilot-in-the-Loop Oscillations (PIO); Background and Classifications

PIO is a phenomenon in the field of Handling Qualities of aircraft which has been encountered and studied well before the advent of active control technology and fly-by-wire flight control systems. Its origin is a misadaptation between the pilot and the aircraft during some task in which tight closed-loop control of the aircraft is required from the pilot, with the aircraft not responding to pilot commands as expected by the pilot himself. This situation can trigger a pilot action capable of driving the aircraft out of pilot control, which in some cases can only be recovered by the pilot releasing the column and exiting from the control loop.

For the active role played by the pilot during the PIO, the original significance given to the acronym was Pilot Induced Oscillations. A more rigorous analysis of the causes of PIO highlighted the fact that PIO are indeed caused by a deficient FCS design more than by pilot errors, and the term Aircraft-Pilot Coupling [5] has been recommended for use. More recently, AGARD/RTO Working Group 23 has suggested the expression Pilot-in-the-Loop Oscillations to satisfy both of the two needs: first to use the PIO abbreviation which is so well-known to the aeronautical community, and second to be more generous to the pilot. At the same time the new proposed expression highlights the fundamental closed-loop behaviour of PIO.

The introduction of fly-by-wire FCS has in a sense exacerbated the problem of PIO, since the multitude of FCS modes, which can be easily designed and included into the new Digital FCS, can very easily disorientate the pilot in the interpretation of the aircraft response to his actions.

Indeed, the three elements which are considered in PIO analysis are:

1. The pilot
2. The aircraft dynamics
3. The trigger
The trigger is defined as an event which can introduce the misadaptation [2]. Examples of the trigger are a mode change or an unexpected non-linear behaviour in the FCS, or a variation in the pilot control behaviour, such as an increase of the pilot gain. This situation has forced the U.S. military authorities to write down since 1982 explicit Flying Qualities Requirements for PIO in their Military Standard Specification Documents [6].

An even greater emphasis is given to PIO detection criteria in the new issues of this Standard [27]. The formal definition of PIO given is:

*There shall be no tendency for pilot-induced oscillations, that is, sustained or uncontrollable oscillations resulting from the efforts of the pilot to control the airplane*

Because of the highly destructive potential of the PIO phenomenon a great effort has been spent in the last years in many research programs both in USA and Europe [28, 26, 5] to study PIO, in order to derive methods which will be able to predict the tendency of aircraft to develop PIO. As defined in the MIL specs, PIO is an umbrella under which the same phenomenon (closed-loop pilot vehicle oscillation) can show with very different behaviours, mainly depending on the underlying cause of the PIO occurrence.

A classification of PIO (from [5]) is given below. It takes into account some possible different behaviours of the closed-loop pilot vehicle system during the PIO.

In the given classification three different behaviours are recognised, leading to three PIO categories:

**PIO Category I**

The closed-loop pilot vehicle system has a linear behaviour. The 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 to prevent PIO in this category.

**PIO Category II**

The closed-loop pilot vehicle system has a non-linear behaviour, mainly characterised by the saturation of position or rate limited elements. These PIOs can in general be modeled as linear events in which an identifiable nonlinear contribution may be treated separately.
PIO Category III

The closed-loop pilot vehicle system has a highly non-linear behaviour, with no further peculiar characteristic. These PIOs rarely occur and are difficult to recognize. When they do occur, the PIOs in this category are the most severe.

This classification allows to categorise PIO detection criteria according to their potentiality to reveal the PIO tendency for the various categories.

PIO Criteria Prerequisites

The National Research Council’s Committee on the Effects of Aircraft-Pilot Coupling on Flight Safety [29] defined three prerequisites for PIO prediction criteria. These prerequisites are:

Validity

“implies that a criterion embodies properties and characteristics that define the environment of interest and are associated with parameter spaces covering the vast majority of known cases….The criterion must relate to closed-loop, high-gain, aggressive, urgent, and precise pilot-control behavior.”

Selectivity

“demands that the criterion differentiate sharply between ‘good’ and ‘bad’ systems…. The most important selectivity feature is the capability of distinguishing configurations that may be susceptible to severe PIOs from those that are not.”

Ready applicability

“requires that the criterion be easily and conveniently applied. Expression of the criterion in terms of readily available system parameters should be compact.”

In the next section we present a survey of some PIO prediction criteria which have been proposed by the research community.

2.3 Prominent PIO prediction criteria

The main objective for developing PIO criteria is to use them as design guidelines, in order to prevent PIO in newly designed aircraft. Another benefit of PIO criteria is from their application to flight test data, where analysis of data can highlight potential problems not emerged during the development phase. Finally, new PIO detection criteria have been proposed in the last year, which claim to be able to identify a PIO in flight, thus allowing a warning signal to be delivered
to the pilot or a corrective action to be taken by an automatic flight control system; these criteria are not addressed in this report, since they will be analysed in other reports of FM/AG12.

The databases used for the generation and validation of PIO criteria have been established in several research programs which have involved both piloted simulations and flight tests with variable stability aircraft (in-flight simulations). Most of the experiments were aimed at the analysis of linear effects in the augmented aircraft dynamics, such as the Neal-Smith [8], LAHOS [9], HAVE PIO [10], HAVE CONTROL [11]. Incidents such as those of the YF22 and Gripen have highlighted the strong impact that rate limits in the actuator or flight control system dynamics can have on the generation of PIO. As a consequence in the last years some experiments to study the influence of rate limiters on PIO were conducted, such as the HAVE LIMITS [12], and a German/Swedish study on the FOSIM flight simulator [13].

The review of criteria for the analysis and prediction of PIO will be presented according to the given classification of PIO, in Category I and II PIO. For Category III PIO no specific detection criterion has been proposed by researchers, therefore this Category will not be analysed in this report.

PIO detection criteria, which have been proposed by the Handling Qualities and Flight Control research community in the past years [29], are summarized as follows:

**Category I PIO**
- Bandwidth/Phase Delay
- Gibson Gain/Phase Templates & Average Phase Rate
- Pitch Attitude Dropback
- Neal-Smith with Requirements Adjusted by Moscow Aviation Institute
- Time Domain Neal-Smith
- Smith-Geddes for Attitude Dominant PIOs
- Hess Pilot Proprioceptive Feedback PSD Templates
- Röger Criterion [56]

**Category II PIO**
- Bandwidth/Phase Delay with amplitude sensitivity
- Open Loop Onset Point (OLOP)
- Hess Pilot Proprioceptive Feedback PSD Templates
- Time Domain Neal-Smith
2.3.1 Category I PIO Criteria

The most prominent criteria [1, 5] presented in this report are:

1. Neal-Smith Criterion [4].
2. Bandwidth/Phase Delay, [16].
3. Smith-Geddes, [17, 18, 19].
4. Gibson Average Phase Rate/\omega_{180} + Gain/Phase Template, [20, 21, 22].
5. Gibson Time Domain [4].

Some of the above listed criteria are good indicators of the tendency of the aircraft to PIO, as will be shown in the following.

All these criteria, originally designed for ‘normal’ handling quality assessment, address stability aspects of closed-loop aircraft-pilot systems.

The Neal-Smith and Smith-Geddes criteria define a pilot model and use it for the analysis of the closed-loop system. The bandwidth/phase delay and phase rate criteria only use the open-loop aircraft with no direct model of the pilot. Implicit inclusion of the pilot is obtained by plotting some parameters of the aircraft model into plots where boundaries of PIO proneness/safety have been derived from the analysis of the parameters of configurations whose PIO properties were known from piloted tests.

Major research effort in the past has been on deriving criteria for the pitch axis, due to the maximum importance of stability and control in this axis for the safe operation of the aircraft. Therefore in the following we will present examples of application of the PIO criteria to the pitch axis. Applicability of the criteria to the roll axis is a matter of current research, as well as their extension to transport aircraft.

2.3.2 Category II PIO Criteria

The most prominent criteria presented in this report are:

1. Time Domain Neal-Smith Criterion (TDNS)
2. Open Loop Onset Point Criterion (OLOP)

The Category II PIO phenomena are characterised by quasilinear pilot-vehicle system oscillations. In these events, the main nonlinear effect is actuator rate and/or position limiting. The rate limiting causes an additional time delay which can have a catastrophic influence on the aircraft handling qualities. The delay due to rate limiting can easily be identified as the
cause for the PIO, but its magnitude in a specific flight control system is difficult to predict. The above mentioned criteria may predict the tendency for Category II PIO. The first one is a method based on the time domain, while the last one is based on frequency domain analysis. Like the Category I PIO criteria, also the above mentioned criteria address stability aspects of the closed-loop aircraft pilot system. For Category II PIO, the focus is now on the nonlinear behaviour induced by rate limiters. The TDNS criterion may, however, also be applied to more general nonlinearities. All Category II PIO criteria use a defined pilot model with different complexity.

2.3.3 Criterion Evaluation

2.3.3.1 Category I PIO

In the following pages a quantitative evaluation of the different category I PIO prediction criteria is presented, to complement the description of the methods. The evaluation is based on the use of the following table, where the number of cases predicted to be PIO prone/free is compared to the actual number of flight test PIO.

<table>
<thead>
<tr>
<th>Number of cases</th>
<th>Flight test PIO (Mean PIOR&gt;2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PIO prediction</td>
<td>NO PIO</td>
</tr>
</tbody>
</table>

Table 1: Evaluation of PIO prediction.

From the numbers in the table it is possible to evaluate the effectiveness of the PIO criteria in predicting PIO, according to different effectiveness measures. Two indices of effectiveness proposed in ref. [27] are the global success rate, i.e. the percentage of cases which are correctly predicted to be PIO free or prone, and an index of conservatism, i.e. the percentage of cases predicted PIO prone which have actually undergone PIO in reality with respect to the total number of predicted PIO prone cases:

1) Global success rate  = (B+D)/(A+B+C+D)
2) Index of conservatism = D/(C+D)
In ref. [3] it was proposed to add a further significant index of effectiveness, the percentage of cases which are predicted by the criterion to be PIO prone, with respect to the total number of flight test PIO cases:

I3) Safety index = \( \frac{D}{A+D} \)

The aim is to maximise this measure, since failing to identify cases which can produce PIO can lead to very dangerous situations. It is interesting to note that index I2 highlights the conservatism of the method (the higher the index the less conservative the method is). The index indicates the probability that a configuration which has been identified as PIO prone by this method will actually develop a PIO in flight. Index I3 highlights how safe the use of the method is, indicating the probability that PIO prone configurations are identified by the method.

The databases used for the assessment of the PIO criteria are the three landing databases:

<table>
<thead>
<tr>
<th>Database</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>LAHOS</td>
<td>Landing High Order System: Influence of high order effects on landing and approach handling qualities, 49 configurations, [9]</td>
</tr>
<tr>
<td>HAVE PIO</td>
<td>PIO investigations during landing, 18 configurations, [10]</td>
</tr>
<tr>
<td>HAVE CONTROL</td>
<td>PIO investigations during landing, 12 configurations, [11]</td>
</tr>
</tbody>
</table>

*Table 2: Landing databases for assessment of PIO criteria.*

2.3.3.2 Category II PIO

Evaluation of the Category II PIO criteria, to complement the background of the method, will be done by means of a qualitative description.
3. Category I PIO Criteria Evaluation

3.1 General

This part provides a description of the evaluation of the most prominent Category I PIO susceptibility criteria as defined in chapter 2. Each criterion will be highlighted by its theoretical background followed by an evaluation of its effectiveness to predict PIO for three databases (paragraphs 3.2 to 3.6). The results of the criteria evaluation are finally discussed and summarized (3.7).

3.2 Neal-Smith Criterion

3.2.1 Criterion Background

The Neal-Smith criterion for closed-loop systems was originally developed for highly augmented fighter aircraft performing precision pitch attitude tracking tasks [14]. The criterion includes a pilot model that contains a gain, lead/lag compensation and a time delay. Definition of the pilot model is done using a certain performance standard or degree of aggressiveness of the pilot, which is characterised by the bandwidth frequency \( \omega_{bw} \). The pilot model parameters must be adjusted so that the closed-loop frequency response satisfies the following requirements:

- the aircraft-pilot phase angle at the bandwidth frequency must be \(-90^\circ\).
- the low frequency amplitude droop must be less than \(-3\) dB.

To apply the criterion, the following steps have to be followed:

1. Specification of the bandwidth appropriate for the task:

   \[
   \begin{array}{|c|c|}
   \hline
   \text{Category A flight phases:} & \omega_{bw} = 3.5 \text{ rad/sec} \\
   \text{Category B and C flight phases:} & \omega_{bw} = 1.5 \text{ rad/sec} \\
   \text{Category C landing phase:} & \omega_{bw} = 2.5 \text{ rad/sec} \\
   \hline
   \end{array}
   \]

2. Adjustment of the parameters of the pilot model to meet the performance standard defined by the bandwidth frequency \( \omega_{bw} \) using a fixed pilot model time delay of 0.3 seconds.
3. Determination of the pilot phase compensation and closed-loop resonance and comparison to the proposed handling qualities boundaries (Figure 1).

The criterion was extended to the approach and landing tasks using the databases in Table 2. This resulted into new handling quality boundaries that provide a good correlation between the predictions of the criterion and the Cooper Harper ratings of about 90%.

3.2.2 Criterion Evaluation

Figure 1 presents the evaluation of the Neal-Smith criterion with the three databases presented in Table 2 clarifying the correlation between the criterion parameters and PIO ratings obtained within the experiments. The data indicates that the modified Neal-Smith boundaries are well suited to predict PIO during the landing task.

From the figure it can be seen that if the criterion parameters are located within the Level 1 area, the PIO rating of a configuration is very likely to be less than 2.5.

In Table 3 a summary of the results of the application of the Neal-Smith criterion to the three landing databases is presented.
<table>
<thead>
<tr>
<th>Number of cases</th>
<th>Flight test PIO (Mean PIOR&gt;2)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>NO PIO</td>
</tr>
<tr>
<td>PIO prediction by Neal-Smith</td>
<td>NO PIO</td>
</tr>
<tr>
<td>PIO</td>
<td>PIOC</td>
</tr>
</tbody>
</table>

Table 3: PIO prediction with the Neal-Smith criterion.

From the numbers in Table 3 it is possible to evaluate the value of the three effectiveness indices introduced above:

1) Global success rate (BD/ABCD) = 42/67 = 81.6%
2) Index of conservatism (D/CD) = 36/60 = 60%
3) Safety index (D/AD) = 36/37 = 97.3%

### 3.3 Bandwidth / Phase Delay Criterion

#### 3.3.1 Criterion Background

The bandwidth/phase delay criterion was developed using the Neal-Smith database for category A flight phases and the LAHOS database for category C flight phases [15, 27]. This criterion is based on the analysis of the aircraft attitude transfer function. No pilot model is used. Two parameters must be computed from the stick force to attitude transfer function:

1. the bandwidth \( \omega_{bw} \), defined as the frequency at which the phase margin is 45° or the gain margin is 6 dB, whichever frequency is lower [15]; the physical interpretation of bandwidth is the highest frequency for which the aircraft will respond to pilot commands. A pilot trying to control the aircraft at a higher frequency would raise his gain so much that instability will occur.

2. the phase delay \( \tau_p \), defined as \( \tau_p = \frac{\Phi(2\omega_{180}) - \Phi(\omega_{180})}{2\omega_{180}} \frac{\pi}{180\text{deg}} \). This is a measure of the slope of the phase angle at frequencies above the bandwidth. A higher phase delay implies that a pilot trying to control the aircraft above the bandwidth will find a rapidly reducing phase margin. Thus instability is again likely to occur. This parameter is the most important with respect to PIO prediction. Cases whose \( \tau_p \) is above a prescribed value are predicted PIO prone. The boundary value depends on the aircraft class and flight phase.

The steps involved in the application of the criterion are:
1. Compute the two criterion parameters from the stick force to attitude transfer function:
2. Plot the two parameters in the criterion plane and compare them to the boundary for PIO.

A thorough analysis of the bandwidth/phase delay criterion is presented in ref. [27], where the inclusion of two secondary parameters, the flight path bandwidth and the dropback parameter was suggested to cope with some cases not well predicted by the primary parameters. In particular an excessive dropback indicates that a configuration can be PIO prone even if its phase delay satisfies the prescribed boundary.

3.3.2 Criterion Evaluation

Figure 2 presents the evaluation of the bandwidth/phase delay criterion with the three databases presented in Table 2 clarifying the correlation between the criterion parameters and PIO ratings obtained within the experiments.

\[\text{Figure 2: Application of the bandwidth/phase delay criterion to the landing databases LAHOS, HAVE PIO, HAVE CONTROL.}\]

In Table 4 a summary of the results of the application of the bandwidth criterion by Mitchell and Hoh to the three landing databases is presented.
Table 4: PIO prediction with the Bandwidth-Phase Delay criterion.

<table>
<thead>
<tr>
<th>Number of cases</th>
<th>Flight test PIO (Mean PIOR&gt;2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NO PIO</td>
<td>28 (B)</td>
</tr>
<tr>
<td>PIO</td>
<td>4 (C)</td>
</tr>
<tr>
<td>PIO prediction</td>
<td>10 (A)</td>
</tr>
<tr>
<td>NO PIO</td>
<td>34 (D)</td>
</tr>
</tbody>
</table>

From the numbers in Table 4 it is possible to evaluate the value of the three effectiveness indices introduced above:

I1) Global success rate (BD/ABCD) = 62/76 = 81.6%
I2) Index of conservatism (D/CD) = 34/38 = 89.5%
I3) Safety index (D/AD) = 34/44 = 77.3%

These figures are reasonably good for a PIO prediction criterion.

3.4 Smith-Geddes Criterion

3.4.1 Criterion Background

Three types of PIO are considered by Ralph Smith [17]:

Type I Initiated by resonance of the closed-loop aircraft-pilot system during attitude tracking. PIO triggered by switching from attitude to normal acceleration control.

Type II Initiated by resonant open-loop dynamics, such as due to low damping.

Type III Initiated by resonance of the closed-loop aircraft-pilot system during attitude tracking, regardless of acceleration dynamics without any switching.

A PIO criterion based on a simple procedure has been proposed by Ralph Smith for prediction of the attitude-dominant type III PIO. The criterion uses a very simple linear formula for the aircraft-pilot crossover frequency \( \omega_{cr} \), based on the crossover frequency data of single axis tracking tasks [25]. The crossover criterion frequency \( \omega_{cr} \) depends on the average slope \( S \) of the aircraft amplitude response in the crossover region according to the formula:

\[
\omega_{cr} = 6.0 + 0.24S
\]

For the application of the attitude dominant Smith-Geddes criterion to the pitch axis the following steps have to be performed:
1. Determine the slope of pitch attitude to stick force amplitude response $S$ over the frequency range of 1 to 6 rad/sec;

2. Calculate the crossover criterion frequency $\omega_{cr}$ and the criterion phase angle of pitch attitude to stick force frequency response $\Phi_{cr}$;

3. The aircraft is type III PIO sensitive if $\Phi_{cr} < -160^\circ$ and PIO prone if $\Phi_{cr} < -180^\circ$.

### 3.4.2 Criterion Evaluation

Figure 3 presents the evaluation of the Smith-Geddes criterion with the three databases presented in Table 2 clarifying the correlation between the criterion parameters and PIO ratings obtained within the experiments.

![Figure 3: Application of the Smith-Geddes criterion to the landing databases LAHOS, HAVE PIO, HAVE CONTROL.](image)

<table>
<thead>
<tr>
<th>Number of cases</th>
<th>Flight test PIO (Mean PIOR &gt; 2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NO PIO</td>
<td>PIO</td>
</tr>
<tr>
<td>PIO prediction by Smith-Geddes</td>
<td>NO PIO</td>
</tr>
<tr>
<td></td>
<td>PIO</td>
</tr>
</tbody>
</table>

*Table 5: PIO prediction with the Smith-Geddes criterion.*
From the numbers in Table 5 it is possible to evaluate the value of the three effectiveness indices introduced above:

1) Global success rate (BD/ABCD) = 61/76 = 80.3%
2) Index of conservatism (D/CD) = 37/45 = 82.2%
3) Safety index (D/AD) = 37/44 = 84.1%

From the figures above this criterion is reasonably good in predicting PIO. The Smith-Geddes criterion was validated in the pitch axis using the Neal-Smith database for up-and-away flight [18]. The criterion can be considered to be effective in detecting PIO prone configurations, since all configurations with PIOR higher than three are predicted to be PIO prone. But, a large scattering is found in the data, such as some very good configurations (PIOR 1.5) are predicted to be PIO prone. Thus it appears that the Smith-Geddes criterion parameter $\phi_{cr}$ alone is not sufficient as a PIO indicator. This is confirmed by the fact, that the important influence of the high frequency phase rolloff is not addressed by this criterion. Investigations based on the HAVE PIO database have shown that the crossover frequency $\omega_{cr}$ is highly correlated with the frequency of PIO cases that have occurred [5].

3.5 Phase Rate Criterion and Gain Phase Template (Average Phase Rate)

3.5.1 Criterion Background

The phase rate criterion was introduced as a simple design criterion to predict PIO due to high order effects in modern flight control systems [21]. The phase rate parameter is defined as the gradient of the phase angle with respect to the frequency in the neutral stability region, which means 180° phase delay. Therefore, it is a direct measure of the high frequency phase roll-off. The phase rate parameter has a strong influence on the PIO generation process. A pilot performing a critical task will generally raise his gain to increase the bandwidth available for the task; this causes an increase of the phase delay proportional to the phase rate parameter. Now the pilot feels the aircraft is not responding fast enough to his commands and this induces a further increase of the pilot gain. This situation will in the end drive the pilot into a PIO, since any increase in crossover frequency results in a severe loss of phase margin.

Originally, the phase rate parameter was defined as the local slope of the phase angle around 180° phase delay:

$$PR_{180} = \left. -\frac{\Delta\Phi(\omega)}{\Delta\omega} \right|_{\Phi(\omega)=180\,\text{deg}}$$
But more recently the average phase rate is used [23]. In that case the phase angle slope is determined within a wider frequency range: \( \Delta \omega = 2\omega_{180} - \omega_{180} \), thus taking into account the effect of a greater increase in bandwidth which is the situation we would look to when the PIO process generated by the pilot is initiated. It is obvious that the average phase rate parameter is directly proportional to the phase delay parameter \( \tau_p \) of the bandwidth criterion (see above). Hence, in this context the local phase rate is considered in the following discussion. Minor differences exist between the criterion boundaries for local and average phase rate. For the evaluation of the criterion, the phase rate parameter \( PR_{180} \) in deg/Hz and the neutral stability frequency \( f_{180} \) in Hz have to be determined from the pitch attitude frequency response.

### 3.5.2 Criterion Evaluation

Figure 4 presents the evaluation of the phase rate criterion with the three databases presented in Table 2, clarifying the correlation between the criterion parameters and PIO ratings obtained within the experiments. The figure indicates that the PIO rating of a configuration is very likely less than 2.5 if the criterion parameters are located within the Level 1 area.

Figure 4: Application of the phase rate criterion to the landing databases LAHOS, HAVE PIO, HAVE CONTROL.

The criterion has been modified in the sense that the boundaries of the regions between Levels 1 to 3 have been changed (Figure 4).
The first part of the Average Phase Rate (APR) criterion just described is very similar to the Bandwidth/Phase Delay criterion. A second part of the criterion has been proposed in ref. [22, 23], in order to include an evaluation of the effects of the actual gain of the aircraft dynamics.

This part of the criterion plots the pitch attitude transfer function on a Nichols (gain-phase) diagram with a focus on the "PIO region", i.e. the area with phases ranging in [-200°, -180°]. In this area bounds are given both for the gain at -180° phase and for the slope of the transfer function in the phase range [-200°, -180°]. Figure 5 presents the gain-phase template with the prescribed boundaries, including the evaluation of LAHOS configuration 5_1. It is evident that, contrary to the APR part of the criterion, the gain phase part of the criterion successfully predicts this configuration to be PIO prone. It is worth noting again that the added value of the gain-phase part of the criterion is in the inclusion of a gain driven evaluation criterion.

![Gain-phase template](image)

*Figure 5: The gain phase template part of the Average Phase Rate criterion, with the evaluation of configuration LAHOS 5_1.*

In Table 6 a summary of the results of the application of the Average Phase Rate + gain-phase template criterion by Gibson to the three landing databases is presented.
From the numbers in Table 6 it is possible to evaluate the value of the three effectiveness indices introduced above:

I1) Global success rate (BD/ABCD) = 55/76 = 72.4%
I2) Index of conservatism (D/CD) = 43/63 = 68.3%
I3) Safety index (D/AD) = 43/44 = 97.7%

It is evident that this criterion is highly effective with respect to the safety point of view (index I3).

A further criterion using a template in the gain phase plane has been proposed by Gibson in ref. [20], for handling qualities evaluation. The analysis is performed by plotting the pitch attitude transfer function in the Nichols plane against boundaries derived from a database of configurations with known handling qualities. A relative gain transfer function is plotted, where the attitude gain is scaled such that the 0 dB line is crossed at -120° phase. Areas of particular interest for handling qualities behaviour are labelled in the plot. Other than a satisfactory area, also a PIO area and a "pitch bobble" one are indicated on the template. The satisfactory area is centred on a K/s behaviour of the response, by assuming that this kind of response is particularly well behaved.

Since the criterion parameter is the transfer function itself and not some global parameters, this criterion is not suited to plot a whole set of configurations, because the spread of the graphs on the plot could hide the peculiarities of the single one. On the other hand looking at the whole transfer function can give more indications than just looking at some global parameters.

In Table 7 a summary of the results of the application of the Gibson gain-phase template criterion to the three landing databases is presented.
From the numbers in Table 7 it is possible to evaluate the value of the three effectiveness indices introduced above:

I1) Global success rate (BD/ABCD) = 56/76 = 73.7%
I2) Index of conservatism (D/CD) = 43/62 = 69.4%
I3) Safety index (D/AD) = 43/44 = 97.7%

It is evident that this criterion is highly effective with respect to the safety point of view (index I3).

Figure 6 presents the evaluation of LAHOS configuration 5_1. The gain-phase template criterion correctly predicts the PIO proneness of this configuration. The transfer function exits from the prescribed bounds both in the low frequencies region (above 0dB of relative gain), where attitude dropback is predicted, and in the higher frequency region (below 0dB of relative gain), where the PIO region is crossed.
3.6 Gibson Time Domain Dropback

3.6.1 Criterion Background

Gibson obtained a vast experience in aircraft control and handling qualities on a wide variety of aircraft, both conventional and fly-by-wire, over several decades working on many advanced programs in the Great Britain. His work has lead to many design guidelines and criteria, often referred to as the ‘Gibson Criteria’, some of which have been incorporated in specifications and requirements of both European and American military and commercial regulations.

Gibson’s design guidelines can be split into a time domain and a frequency domain approach. The background of the criteria in the pitch axis is the quality of the combined response characteristics of both pitch attitude and flight path, and how well the combined behavior is when the pilot excites the aircraft through the stick. Many of Gibson’s ideas involve open-loop analysis of the aircraft response. However, the connection with closed-loop control by the pilot is always present, in the end the requirements result in systems that behave like systems whose characteristics are known to be preferable for tight pilot control.

Two important Gibson criteria that are defined in the time domain are addressed here: pitch attitude dropback and flight path angle time delay. Both criteria were developed over a considerable time span, and the latest definitions can be found in ref. [46].

The dropback criterion in its original form was introduced in ref. [20] as one of a set of design guidelines for highly augmented fighter aircraft. A subsequent analysis for transport aircraft is reported in ref. [55]. Originally, it was defined in terms of limiting values of the pitch rate overshoot ratio and the ratio of attitude dropback to steady state pitch rate. The definition of these parameters is shown in Figure 7, which depicts typical responses of a rate command type aircraft to a box-car stick input. The parameters involved in the criterion are the peak pitch rate, \( q_{\text{im}} \), and the attitude dropback, \( DB \), normalized to the steady state pitch rate, \( q_s \), as defined in Figure 7. Dropback is computed as the difference between the pitch attitude at the time the stick is released and the steady state attitude after the stick is released. A positive value of this difference is referred to as dropback, while a negative value is named overshoot. Because of the use of a steady state pitch rate, the criterion is applicable only to pitch rate command and conventional response types with constant velocity (short period approximations).

Regions of typical pilot comments are defined in the criterion plane \( (DB/q_s, q_{\text{im}}/q_s) \) (Figure 8). Here, criterion mappings are related to qualitative descriptions of the response such as abruptness, sluggishness and bobbling. Negative dropback is an indication of sluggishness,
while large positive values of dropback indicate abrupt and bobbling tendencies. Low values of dropback, between 0 and 0.1 sec, are usually considered good. The physical explanation of the criterion is that the satisfactory region is associated with predictability of the open-loop attitude response after a corrective pilot command. Simply stated, the amount of dropback and overshoot indicates how well the aircraft responds to (or ‘follows’) the stick. The criterion was developed for fighters for accurate pitch tracking tasks where ideally there should be no attitude dropback to stick commands, or the nose exactly follows the stick. This, however, can produce a sluggish flight path response and is not optimum for the approach and landing task [54].

The dropback criterion has been interpreted slightly differently by ref. [27]. In this paper, it is noted that dropback as defined by Gibson is influenced by time delay, which is already taken into account in other handling qualities requirements. Therefore, the new form of dropback has been proposed which is more focused on the mid-frequency range of the attitude response. Pitch attitude dropback is here defined as the difference between the peak pitch attitude and the steady state pitch attitude after the stick is released. Thus (Figure 7):

\[
DB = \theta_m - \theta_s
\]

This eliminates from the dropback parameter the effect of the time delay on the response. A single boundary is defined in the criterion plane, dividing it into the two regions of **Acceptable**...
dropback and Unacceptable dropback. According to ref. [27], which introduced it, this version of dropback is not to be used as a stand-alone PIO criterion. Instead, it must be used to complement the bandwidth criterion, in order to highlight a PIO tendency of configurations with low phase delay and bandwidth.

A further refinement was proposed in ref. [37]. Generally, estimating the parameters needed for the Dropback criterion application from flight test can be hard, since pilot inputs are never shaped as in Figure 7, and steady-state pitch rate will hardly occur during flight. A remedy to this is to move to the frequency domain. Figure 9 depicts a typical pitch rate command type frequency response (note the constant gain for low frequencies indicating a constant steady-state pitch rate when a step input is applied). Frequency responses like this one can be estimated reasonably easily and accurately in flight tests by performing frequency sweeps. The indicator for dropback is now the difference in gain between the peak value of the gain plot and the low-frequency value. When this difference is less than 12 dB, the amount of dropback is considered acceptable. When the difference exceeds 12 dB, and Pitch Attitude Bandwidth is less than 1 radians per second, and Pitch Attitude Phase Delay is less than 150 milliseconds, then PIO is predicted. It is emphasized that this test is defined in conjunction with the bandwidth criterion. It is noted further that in case a phugoid-type mode is present in the aircraft dynamics (e.g. for conventional, unaugmented response-types), a peak in the gain plot can be present at low frequencies (typically < 1 radians per second). When this is the case, \( \Delta G(q) \) is determined by taking the difference between the peak and the droop that will be present in the gain plot of \( |q/F_{es}(\omega)| \).

![Bode Plot and Frequency Response](image)

*Figure 9: Frequency-domain definition of dropback using the frequency response of pitch rate to control inceptor force \( q/F_{es}(s) \).*
The second time domain Gibson criterion addressed here is the flight path time delay, \( t_{\gamma} \).

Figure 10 shows how \( t_{\gamma} \) is determined from the flight path response to a step input. This is achieved by taking the best fit tangent to the flight path angle response at around 4 seconds. The flight path time delay is defined by the intersection of the tangent and the time axis. Basically, \( t_{\gamma} \) is a measure of the delay that is observed between stick input and a noticeable flight path response. Ref. [46] suggests that for the landing approach task, \( t_{\gamma} \) should not exceed 1.5 seconds generally and 1.0 seconds for precision flight path control.

3.6.2 Criterion Evaluation

Figure 11 presents the evaluation of the original Gibson time domain dropback criterion with the three databases presented in Table 2, clarifying the correlation between the criterion parameters and PIO ratings obtained within the experiments.
In Table 8 a summary of the results of the application of the Dropback criterion to the three landing databases is presented. For this purpose, a criterion mapping in the satisfactory region (Figure 8) is considered to indicate no PIO susceptibility. A mapping outside this region is considered to indicate PIO susceptibility.

<table>
<thead>
<tr>
<th>Number of cases</th>
<th>Flight test PIO (Mean PIOR&gt;2)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>NO PIO</td>
</tr>
<tr>
<td>PIO prediction</td>
<td>NO PIO</td>
</tr>
<tr>
<td>by Gibson</td>
<td>PIO</td>
</tr>
</tbody>
</table>

*Table 8: PIO prediction with Gibson dropback criterion.*

From the numbers in Table 8 it is possible to evaluate the value of the three effectiveness indices introduced above:

1) Global success rate \(\frac{BD}{ABCD} = \frac{47}{76} = 61.8\%\)

2) Index of conservatism \(\frac{D}{CD} = \frac{28}{41} = 68.3\%\)

3) Safety index \(\frac{D}{AD} = \frac{28}{44} = 63.6\%\)

Figure 12 presents the evaluation of the modified dropback criterion as defined in ref. [27] using the same data, clarifying the correlation between the criterion parameters and PIO ratings obtained within the experiments.

*Figure 12: Application of the modified dropback criterion to the landing databases LAHOS, HAVE PIO, HAVE CONTROL*
In Table 9 a summary of the results of the application of the modified Dropback criterion by Mitchell and Hoh to the three landing databases is presented.

<table>
<thead>
<tr>
<th>Number of cases</th>
<th>Flight test PIO (Mean PIOR&gt;2)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>NO PIO</td>
</tr>
<tr>
<td>PIO prediction</td>
<td>NO PIO</td>
</tr>
<tr>
<td>modified dropback</td>
<td>26 (B)</td>
</tr>
<tr>
<td></td>
<td>PIO</td>
</tr>
<tr>
<td></td>
<td>6 (C)</td>
</tr>
</tbody>
</table>

Table 9: PIO prediction with modified dropback criterion.

From the numbers in Table 9 it is possible to evaluate the value of the three effectiveness indices introduced above:

I1) Global success rate (BD/ABCD) = 47/76 = 52.6%
I2) Index of conservatism (D/CD) = 14/20 = 70%
I3) Safety index (D/AD) = 14/44 = 31.8%

This performance is not very good. However, the test should be used to complement the bandwidth criterion according to ref. [27]. The evaluation presented here is merely to show the effect of the modified definition of dropback on the criterion results.

3.7 Discussion of Category I PIO Criteria

The criteria presented above are discussed with respect to their effectiveness in Category I PIO prediction and the gaps in the criteria and possible extensions. A general comment is that Category I PIO is adequately predicted by the available criteria. Really good configurations are rated good by all criteria and vice versa. But there are significant differences between the criteria and open questions to be discussed.

3.7.1 Criterion Effectiveness

The first four criteria presented in Table 10 are suitable for predicting category I PIO problems, but with different effectiveness with relation to the three indices. The Neal-Smith, Bandwidth-Phase Delay and Smith-Geddes criteria have the highest global success rate, about 81% success cases. The Bandwidth-Phase Delay is also the less conservative criterion, with 89.5%.

With a lower global success rate, about 73% success cases, follow the Phase Rate and the Gibson Frequency Domain template. These criteria, in addition to the Neal-Smith criteria, are
<table>
<thead>
<tr>
<th>PIO criterion</th>
<th>Global success rate [%]</th>
<th>Conservatism [%]</th>
<th>Safety [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Neal-Smith</td>
<td>81.6</td>
<td>60</td>
<td>97.3</td>
</tr>
<tr>
<td>2. Bandwidth-Phase Delay</td>
<td>81.6</td>
<td>89.5</td>
<td>77.3</td>
</tr>
<tr>
<td>3. Smith-Geddes</td>
<td>80.3</td>
<td>82.2</td>
<td>84.1</td>
</tr>
<tr>
<td>4. Average Phase Rate + Gain-Phase</td>
<td>72.4</td>
<td>68.3</td>
<td>97.7</td>
</tr>
<tr>
<td>5. Gibson frequency domain template</td>
<td>73.7</td>
<td>69.4</td>
<td>97.7</td>
</tr>
<tr>
<td>6. Dropback</td>
<td>61.8</td>
<td>68.3</td>
<td>63.6</td>
</tr>
<tr>
<td>7. Modified dropback</td>
<td>52.6</td>
<td>70</td>
<td>31.8</td>
</tr>
</tbody>
</table>

Table 10: Performance indices of Category I PIO prediction criteria.

all characterised by a high value of the safety index, above 90%. The two Gibson criteria, that are the only criteria that include a bound for the gain of the transfer function, share an almost complete success rate of 97.7% for the safety index. Therefore it is suggested to include these criteria in a PIO analysis. The Neal-Smith criterion appears to be the most effective PIO criterion in the pitch axis since it predicts PIO and bobbling tendencies.

Apart from PIO, also other phenomena such as bobbling tendencies, although not really considered as PIO, can be annoying for the pilot. In order to show the capability of detecting bobbling tendencies, one specific configuration, LAHOS 5_1, is considered more in detail, and can be identified in the criterion graphics. This configuration was rated with PIOR 3 after two runs with the following typical pilot comments:

*Tendency to bobble, low frequency PIO during landing.*

The Smith-Geddes criterion does not represent these pilot ratings, the configuration is predicted to be PIO free. The bandwidth/phase delay also does not predict the PIO potential of this configuration, but the bobbling is indicated due to the excessive dropback, which has been suggested as a complementary criterion. The Neal-Smith criterion also indicates the bobbling tendency. The phase rate criterion predicts the PIO potential since the gain-phase template requirement is not satisfied. The Gibson frequency domain criterion also predicts unsatisfactory behaviour from both the low gain margin and the high attitude dropback.
3.7.2 Criterion Gaps and Extensions

All the presented criteria address only PIO caused by pilot control of aircraft attitude, while it is generally accepted that acceleration cues are also important for the pilot. The type I PIO criterion by R. Smith assumes that the PIO is triggered by switching from attitude to acceleration control. The computations required for application of this criterion are much more complex than those of the very simple type III PIO criterion presented here.

Some criteria address the gain of the attitude transfer function. This is done either directly as a bound for the gain at the -180° frequency, as in the two Gibson criteria in the frequency domain. It is worth noting that these criteria are also those with the highest values of the safety index, all above 90%.

Regarding practical applications of the bandwidth/phase delay criterion to flight test data problems can arise, since the measured frequency response data might be doubtful in the high frequency range of $2\omega_{180}$ [24]. The computation of the average magnitude slope for the Smith-Geddes criterion can be no longer meaningful for configurations with low damped modes, such as flexible modes, within the frequency range of interest, 1 to 6 rad/sec. Indeed, these cases can show a significant variation of the magnitude slope with respect to the average value, in the range of the low damped modes.
4. Category II PIO Criteria Evaluation

4.1 General

This part provides a description of the evaluation of the most prominent Category II PIO susceptibility criteria as defined in chapter 2. The criteria will be highlighted by their theoretical background followed by an evaluation of their effectiveness to predict PIO (4.2, 4.3).

4.2 Time Domain Neal-Smith Criterion

4.2.1 Criterion Background

The Time Domain Neal-Smith Criterion was presented in “A Quantitative Criterion for Pilot-Induced Oscillations: Time Domain Neal-Smith Criterion” by Bailey and Bidlack [45]. The criterion is based on the Neal-Smith handling qualities criterion in the frequency domain (e.g. ref. [8]). For the extension to evaluation of PIO tendencies, the time domain was chosen with the intention to allow evaluation of nonlinear effects in exactly the same way as a linear system. A valuable contribution to the further development of the Time Domain Neal-Smith Criterion is given in ref. [39], “An analysis of the Time-Domain Neal-Smith Criterion” by Foringer and Leggett.

The criterion uses simulation with a pilot model performing a closed-loop tracking task.

A 5° step in commanded pitch attitude $\theta_c$ is issued 0.25 s into the simulation. The pilot model must acquire the commanded pitch angle at exactly the time $D$ s after the start of the simulation. The angle is considered as acquired at the first time when the pitch attitude error is less than $1/40$ of the step command, i.e. $0.125^\circ$. The commanded pitch angle must then be tracked as closely as possible. The Root Mean Square of the pitch tracking error, $rms \theta_e$, is calculated from the time of acquisition until 5 s from the simulation start.

Figure 13: The closed-loop tracking task.
The performance of the pilot model must be optimized using two constraints:

1. The commanded angle must be acquired at $D_s$ after the simulation start. A low value of $D$ forces the pilot to acquire the target quickly.
2. The $rms\theta_e$ must be minimised. This requires a minimum of overshoot and oscillation.

The parameter $D$, the acquisition time, is related to the bandwidth frequency $\omega_{BW}$ in the frequency domain Neal-Smith criterion in the following way:

$$\omega_{BW} = -(1/(D - 0.25)) \cdot \ln(1/40)$$

For example, a smaller $D$ corresponds to a higher bandwidth frequency and thus a more demanding task.

The optimisation is accomplished by changing two parameters in the pilot model, the gain $K_p$ and the pilot compensation parameter $T_L$. Positive values of $T_L$ correspond to pilot lead compensation, and the pilot model will look as follows:

$$\delta_p = e^{-\tau} \cdot K_p (T_L s + 1) \cdot \theta_e$$

Negative values of $T_L$ represent pilot lead-lag compensation, which will make the pilot model look like this:

$$\delta_p = e^{-\tau} \cdot K_p \frac{t_{p1}s + 1}{t_{p2}s + 1} \cdot \theta_e$$

where $t_{p2} = (1/\omega_{BW} - T_L)$, $t_{p1} = (1/t_{p2}\omega_{BW}^2)$ and $\omega_{BW} = -(1/(D - 0.25)) \cdot \ln(1/40)$.

The pilot time delay $\tau$ is always 300 ms.

A mechanisation of the aircraft model, pilot model and tracking task can be made in Simulink as in Figure 14. This Simulink system can then be called by a Matlab program that searches for the optimum values of $K_p$ and $T_L$ for each value of $D$. The data that are then used in the evaluation are $rms\theta_e$ and the pilot lead or lag compensation angle, $\angle_{p_c}$. The compensation angle is calculated from $T_L$ and $\omega_{BW}$.
\[ \angle_{pc} = 57.3 \tan^{-1}(T_L \omega_{BW}) \quad \text{for } T_L > 0. \]
\[ \angle_{pc} = 57.3 \tan^{-1}(t_{p1} \omega_{BW}) - 57.3 \tan^{-1}(t_{p2} \omega_{BW}) \quad \text{for } T_L < 0. \]

Figure 14: A typical Simulink system for use of the criterion.\(^1\)

An extra 50 ms has been added to the pilot time delay in Figure 14 to account for the time delay of FFA’s flight simulator FOSIM. The AIAA paper mentioned is ref. [39]. A number of simulations are needed to find the optimum for each value of \( D \), and if many configurations or many points in the envelope are to be checked, use of the criterion is very time consuming. A powerful computer and a fast search/optimisation method are needed (FFA’s current set-up is not the ultimate here.) An alternative strategy for finding the optimum values, also using Simulink, is described by van der Weerd in ref. [53].

\(^1\) Note that the location of the elevator rate limiter and elevator position limiter should be switched.
In the diagram above it can be seen that the $5^\circ$ step command comes in at 0.25 s, and that it takes a little while for the pilot model to react. The angle is acquired at 1.05 s, and $rms \theta$ is calculated to $0.8224^\circ$ for the remaining time which means that the compensation is fairly close to the optimum for this configuration (see Figure 16).

The criterion can be used for both handling qualities and PIO susceptibility analysis. For handling qualities, Bailey and Bidlack used the Neal-Smith database to come up with the following diagram:
The points in the diagram correspond to $D = 1.05$ s. It should be noted that all the configurations in the diagram above are entirely linear. Configurations that have rate or position limits on their control surfaces may not be able to attain a $D$ of 1.05 s regardless of pilot gain and compensation. How this affects the possibility to use the criterion for HQ evaluation will not be entered into here.

For the prediction of PIO susceptibility, the criterion is based on the assumption that when $D$ is lowered for a PIO prone configuration, there will be a sudden and dramatic change in how tracking performance deteriorates with respect to a change in $D$. At higher values of $D$, $\text{rms} \theta_e$ will smoothly and gradually increase when $D$ is lowered. Then at some smaller $D$, $\text{rms} \theta_e$ will start to increase much more quickly for a decrease in $D$. This would correspond to a large value of the second derivative of $\text{rms} \theta_e$ with respect to $D$, i.e. $\frac{\partial^2 \text{rms} \theta_e}{\partial D^2}$. Bailey and Bidlack had only linear databases available, and from these deduced that a second derivative of $100 \text{ deg/s}^2$ at some value of $D \geq 0.9$ s would indicate that a configuration was PIO prone, while a configuration would be PIO resistant if the second derivative did not exceed $100 \text{ deg/s}^2$.

Bailey and Bidlack also used their criterion on two hypothetical configurations with rate limited elevators, one of them also degraded by a 200 ms time delay. It was clearly shown that the rate limit created a handling qualities cliff, a large $\frac{\partial^2 \text{rms} \theta_e}{\partial D^2}$ at some $D$. In connection with this it was suggested that the value of $D$ at which the handling qualities cliff occurs should be incorporated as a parameter for the criterion. As will be explained below, it has later been found that this can not be done in a simple way.

In ref. [39], the criterion is compared to the HAVE LIMITS database, which was not available when the criterion was first conceived. The HAVE LIMITS database is a result of an in-flight simulation campaign at the USAF Test Pilot School in 1997, sponsored by the Wright Laboratory. Three basic configurations were flown in the Calspan NT-33. One solid Level 1 aircraft (designated 2D), one Level 2 aircraft (2P) and an unstable aircraft augmented to Level 1 (2DU). All were flown with elevator rate limits of 10, 20, 30, 40, 50, 60 and 157 deg/s. Cooper-Harper and PIO ratings from the performance of a discrete tracking task in the HUD were used for comparison with the criterion. It was shown that the metric proposed by Bailey and Bidlack was not satisfactory for nonlinear configurations. By reducing $D$ it was possible to make $\frac{\partial^2 \text{rms} \theta_e}{\partial D^2}$ exceed 100 deg/s$^2$ even for the PIO resistant configurations. When a limit for $D$ was added to the criterion as proposed by Bailey and Bidlack, it was found that this limit had to be set differently for the three baseline configurations. Therefore a limit like this was not very
useful. Finally, based on the HAVE LIMITS database, Foringer and Legget in ref. [39] proposed a number of constraints for $\text{rms} \theta_{e}$ at the smallest feasible $D$ vs. $D$, maximum $\frac{\partial \text{rms} \theta_{e}}{\partial D}$ vs. $D$, maximum $\frac{\partial^{2} \text{rms} \theta_{e}}{\partial D^{2}}$ vs. $D$ and $\text{rms} \theta_{e}$ at the smallest feasible $D$ vs. $D$ for commanded pitch angles $\theta_{c} = 2.5^\circ$ and $\theta_{c} = 10^\circ$. These are shown in the diagrams below. They state, however, that more data is needed to determine if the changes are sufficient to make the criterion satisfactory for the prediction of PIO.

![Figure 17: Constraints for $\text{rms} \theta_{e}$ at the smallest feasible $D$ vs. $D$, $\theta_{c} = 5^\circ$.](image1)

![Figure 18: Constraints for minimum $\frac{\partial \text{rms} \theta_{e}}{\partial D}$ vs. $D$, $\theta_{c} = 5^\circ$.](image2)
Figure 19: Constraints for maximum \( \frac{\partial^2 \text{rms} \theta_c}{\partial D^2} \) vs. \( D \), \( \theta_c = 5^\circ \).

Figure 20: Constraints for \( \text{rms} \theta_c \) at the smallest feasible \( D \) vs. \( D \), \( \theta_c = 2.5^\circ \).
4.2.2 Criterion Evaluation

According to available documentation, i.e. ref. [45] and ref. [39], the original criterion works well for entirely linear configurations. However, it was the wish to handle nonlinear configurations that was the motive to develop the criterion. A step in the right direction has been taken by the work presented in ref. [39]. More nonlinear data, preferably from in-flight simulation or flight tests, is needed for the validation of the criterion.

Below are a few results of the application of the criterion on nonlinear configurations tested in FFA’s FOSIM. Some data needed for the constraints suggested in ref. [39] have not been plotted here, but the ones that are shown will be discussed.

The nonlinearities of the configurations are rate limits of 565, 35 and 15 deg/s respectively, and elevator deflection limits of ±25° approximately. The linear dynamics are Level 1 according to Gibson’s Phase Rate Criterion and according to the Time Domain Neal-Smith Criterion. However, the elevator rate and deflection limits in combination with a not very effective elevator mean that a very high $K_p$ is needed to acquire the tracking command for the lower values of $D$, even for the highest rate limit. This way, $\text{rms} \theta_e$ is pushed up.
As can be seen, this system exceeds the $\frac{\partial^2 \text{rms} \theta_c}{\partial D^2}$ of 100 deg/s$^2$. The main cause here is that $K_p$ is raised to give very abrupt pilot response, in order to compensate for the elevator deflection limits and ineffective elevator. This system was given Level 1 to Level 2 ratings in the simulator and was given PIO ratings of 1 and 2. According to the limits for $\frac{\partial^2 \text{rms} \theta_c}{\partial D^2}$ and $\text{rms} \theta_c$ from ref. [39], this configuration is not PIO prone.

*Figure 22: 565 deg/s rate limit.*
For this configuration $\frac{\partial^2 \text{rms} \theta_e}{\partial D^2}$ clearly exceeds 100 deg/s$^2$. It was evaluated against the OLOP criterion and was found not to be PIO prone. It was given PIO ratings of 1 to 3 in the simulator, with a mean of a little more than 2. According to the limits for $\frac{\partial^2 \text{rms} \theta_e}{\partial D^2}$ and $\text{rms} \theta_e$ from ref. [39] the configuration is not PIO prone.
This configuration is PIO prone according to the limits for $\frac{\partial^2 \text{rms} \theta_e}{\partial D^2}$ and $\text{rms} \theta_e$ from ref. [39], and was also pointed out as PIO prone by the OLOP criterion. It got a mean PIO rating of 3.5 in the simulator, with all pilots giving it either a 3 or a 4.

One weakness of the Time Domain Neal-Smith Criterion is that any small fluctuation in the $\text{rms} \theta_e$ curve results in a very shaky $\frac{\partial^2 \text{rms} \theta_e}{\partial D^2}$ curve. Another weakness is that the $\frac{\partial^2 \text{rms} \theta_e}{\partial D^2}$ curve can be changed substantially by changing the step in D. In ref. [39] a step in D of 0.025 s is mentioned as appropriate. A fixed step in D should probably be defined as a part of the criterion. The recommended step of 0.025 s has been used here.

It is clear that the work by Foringer and Legget has improved the accuracy of the criterion for nonlinear configurations. Using their constraints has resulted in a fairly good agreement both with the OLOP criterion and the simulator results in the examples above. The state of the criterion is probably still such that the use of it is not a way to insure oneself against PIO. Use of the criterion should be seen as a way to increase the knowledge about the configuration that is being studied, and as a step on the way to improve and develop the criterion further. With that in mind, it is strongly advised to use the criterion.
4.3 Open Loop Onset Point Criterion (OLOP)

4.3.1 Criterion Background

The OLOP criterion is a new Category II PIO prediction criterion being developed at DLR [13, 47, 48, 49]. OLOP means open-loop onset point and it refers to the onset point of a rate limiting element displayed in a Nichols chart. Currently, OLOP is the only validated Category II PIO criterion.

The development of the OLOP criterion is based on the describing function technique. The describing function of an isolated rate limiting element has been developed using a Fourier series for the fully developed rate limiting situation (pure triangle output function) [50]. The describing function is dependent on frequency and input amplitude $u_{rl}$, while the amplitude dependence is included in the onset frequency $\omega_{onset} = R / u_{rl}$. The latter is defined as the frequency at which the rate limiter is activated for the first time.

For Category II PIO prediction the rate limiting effects in a closed control loop have to be analysed. Therefore, a method has been developed to calculate the describing function of a rate limited closed-loop system. The application of this method to a highly augmented aircraft with a rate limiter in the feedback loop is presented in Figure 25. The closed-loop system describing function is characterised by a jump phenomenon after rate limiting onset, which can be recognized in a Nichols chart as a significant phase jump. In the presented example the phase jump leads to a dramatic loss of phase and amplitude margin indicating the potential for an instability of the closed-loop system. This instability was verified by a nonlinear simulation in the time domain [48].
In that Nichols chart, the open-loop onset point (OLOP) can be identified as the point where the phase jump starts. Within further studies, the OLOP parameters of a great number of aircraft systems have been determined, indicating that the severity of the jump phenomena in the frequency domain and the corresponding destabilization observed in the time domain are highly correlated with the OLOP location in a Nichols chart.

The OLOP location in a Nichols chart is a measure of the magnitude of the additional time delay due to rate limiting onset. It has been shown by the describing function analysis that the primary effect caused by the activation of a rate limiter is a strong increase in phase delay and a slight decrease in amplitude [49]. If the OLOP is located at high amplitudes the additional phase delay causes an increase in the closed-loop amplitude as demonstrated in the Nichols chart of Figure 26. This increase in closed-loop amplitude provokes a stronger rate saturation and, therefore, further increasing phase delay. This mechanism can lead to a closed-loop instability. For an OLOP located clearly below 0 dB the increasing phase delay does not cause an increase in closed-loop amplitude, so the rate limiting effects are less dramatic.
4.3.2 Criterion Evaluation

For the application of the OLOP criterion the use of the describing function technique is not required. A linear model of the aircraft including the flight control system, the positions of the relevant rate limiter, and the information about maximum stick deflections and maximum rates must be available. The procedure for the evaluation of the OLOP criterion is summarized below [49]:

1. Definition of a simple (high) gain pilot model based on the linear aircraft dynamics.
2. Calculation of the linear closed-loop frequency response from the stick input to the input of the rate limiter.
3. Determination of the closed-loop onset frequency \( \omega_{\text{onset}} \) considering stick and control surface deflection limits.
4. Calculation of the linear open-loop frequency response \( F_{\text{OLOP}}(j\omega) \) and separation into amplitude \( A_0(\omega) \) and phase angle \( \Phi_0(\omega) \).
5. \( \text{OLOP} = [\Phi_0(\omega_{\text{onset}}), A_0(\omega_{\text{onset}})] \).

The pilot model has to be adjusted to the linear aircraft model, which means that the pilot has adapted himself 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 (post transition retention) [32]. The sudden change in closed-loop aircraft behavior may lead to a strong misadaptation of the pilot which can cause an instability of the closed-loop aircraft-pilot system (= PIO).
It is recommended that simple gain pilot modes be used since the pilot usually reacts as a simple gain during a fully developed PIO (synchronous precognitive behaviour) [32]. The pilot gain $K_{pil}(\Phi_{cr})$ has to be adjusted based upon the linear crossover phase angle of the open-loop aircraft-pilot system $\Phi_{cr}$. It is recommended that a gain spectrum from $\Phi_{cr} = -120\text{deg}$ (low pilot gain) up to $\Phi_{cr} = -160\text{deg}$ (high pilot gain) should be applied. This gain spectrum should be used to assess the pilot model gain sensitivity of the aircraft.

The linear open-loop frequency response $F_{OLOP}(jw)$ is determined by cutting the system at the rate limiter and treating the system with rate limiter removed: 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 $y_{OLOP}$. More details on the application of the OLOP criterion are available in references [13, 48, 49]. The introduced procedure is applicable to the pitch and roll axis.

For verification of the OLOP criterion boundary, an off-line analysis of flight experiments was conducted. This analysis was performed using hand aircraft models based on the three lateral databases in Table 9 [49]. Available aircraft (flight control system) models of Category II PIO prone configurations of X-15, YF-16, YF-12 were also used. All these investigations confirmed the OLOP criterion being well suited for Category II PIO prediction in roll, pitch and yaw axes.

These evaluations have shown that for the configurations with forward path and feedback loop rate limiters the OLOP location is highly correlated with PIO susceptibility. This indicates that the OLOP criterion is applicable to both forward path and feedback loop rate limiters using the same PIO boundary.

<table>
<thead>
<tr>
<th>LATHOS</th>
<th>(LATeral High Order System): In-flight simulation program on the NT-33 to study the effects of time delay and prefilter lag in the lateral flight control system [51].</th>
</tr>
</thead>
<tbody>
<tr>
<td>F-18</td>
<td>In-flight simulation program on the NT-33 to identify handling qualities problems of the F-18A prior to its first flight [52].</td>
</tr>
<tr>
<td>YF-16</td>
<td>The famous first flight PIO incident of the YF-16 aircraft including the flight control system modifications [31].</td>
</tr>
</tbody>
</table>

*Table 11: Lateral databases for PIO research.*
After these promising results, the final validation of the OLOP criterion has been performed by evaluating new flight simulator experiments which were especially designed to get a wide OLOP spectrum. This resulted into the FOSIM data [49]. Figure 27 presents the final results of these investigations. In that figure, the differences between the PIO ratings of nonlinear and linear runs \((\text{DPIOR} = \text{PIOR}_{\text{non-linear}} - \text{PIOR}_{\text{linear}})\) were compared with the OLOP boundary. This was possible since all configurations were tested with and without rate limiting.

![Figure 27: Validation of the OLOP criterion using the FOSIM data.](image)

It has been shown that the activation of rate limiters in the feedback loop provides a very strong Category II PIO potential, especially for high flight control system feedback loop gains. Further investigations have shown that Category I and II PIO are not correlated, which means the OLOP criterion is not correlated with the linear PIO criteria [49].
5. Conclusions

In this report prominent PIO susceptibility criteria for the prediction of Category I and II PIOs have been described and evaluated. The criteria that have been assessed are:

**Category I PIO**
1. Neal-Smith
2. Bandwidth-Phase Delay.
4. Gibson Average Phase Rate/$\omega_{180} + \text{Gain/Phase Template}$.
5. Gibson Time Domain Dropback

**Category II PIO**
1. Time Domain Neal-Smith
2. Open Loop Onset Point

The theoretical background has been described first, and an evaluation of the effectiveness of the presented criteria to predict PIO are presented. For Category I PIOs, the evaluation was performed by applying them to three PIO databases.

The results of the Category I PIO criteria evaluation can be summarized as follows:

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Neal-Smith</td>
<td>Most effective PIO indicator, bandwidth sensitivity important</td>
</tr>
<tr>
<td></td>
<td>Modified criterion available in the roll axis.</td>
</tr>
<tr>
<td>Bandwidth/Phase Delay</td>
<td>Effective PIO indicator (high frequency phase rolloff).</td>
</tr>
<tr>
<td></td>
<td>Problems when applied to flight test data.</td>
</tr>
<tr>
<td>Phase Rate (local)</td>
<td>Effective PIO indicator (high frequency phase rolloff).</td>
</tr>
<tr>
<td></td>
<td>Applicable to the roll axis as well.</td>
</tr>
<tr>
<td>Gibson</td>
<td>Effective PIO indicator, especially for safety index</td>
</tr>
</tbody>
</table>

The results of the Category II PIO criteria evaluation can be summarized as follows:

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time Domain Neal-Smith</td>
<td>Still under development</td>
</tr>
<tr>
<td></td>
<td>Currently used to increase knowledge about the system</td>
</tr>
<tr>
<td>Open Loop Onset Point</td>
<td>Promising effective PIO indicator</td>
</tr>
</tbody>
</table>

The prominent PIO criteria show a high degree of success in predicting PIOs for the cases evaluated. As such, all presented criteria may be applied for PIO prediction analysis.
Industrial View

The following presents the views of the industrial participants in the project consortium with regard to the contents of this report.

DASA

Report comments

The report is written well understandable. From an industry point of view one comment though is to be made.

Other than in a research environment sometimes detailed information about criteria is not readily available in an industry environment. For this reason, it would increase readability of the document if more information about how to apply these criteria was included. At this point, the document does not give a guideline for the application of these criteria. This applies also to the description of the physical background, which would help to understand the criterion and its results better.

A deeper description would increase the value in a sense that all relevant information is readily available. Possibly this comment applies better for the envisaged handbook.

Experience on PIO criteria

In present projects, DASA Military Aircraft applies the following PIO criteria:

- Phase rate criterion (average phase rate)
- Absolute amplitude criterion
- Pitch attitude frequency response criterion
- Gibson dropback criterion
- Neal-Smith criterion
- Rögers phase and gain margin criterion

The last three criteria in the list above are used to backup the results of the first four criteria.
Experience with real PIO/handling deficiencies (flight test) exists only with regard to the Neal-Smith and the Röger Criterium. In present projects, the use of the above mentioned criteria during design allowed to exclude PIO tendencies - at least none have been found up to now.

Röger's phase and gain margin criterion

The Röger criterion was successfully applied to a tracking problem of a former combat aircraft and allowed to solve the problem.

It was further on applied for approach and landing of an experimental aircraft, where pilots complained about handling especially during flare, when the normal control laws with attitude feedback on were used. When in two flights the attitude feedback was switched off excellent pilot ratings were obtained.

When other criteria as the Neal-Smith, the Smith-Geddes and the bandwidth criterion of Mitchell/Hoh were applied they failed to identify the difference in behaviour with the two control laws. Whereas the Röger criterion clearly delivered different ratings for the two cases and allowed to successfully design the command filter, which improved landing control to a satisfactory status - overcontrol tendencies were gone.

Manned simulation study at DASA/Dornier

Some years ago, a manned simulation study on handling qualities criteria for modern combat aircraft at DASA/Dornier with five testpilots showed that the Röger criterion can identify PIO tendencies. This study also showed that the Neal-Smith criterion and the phase rate criterion are indeed able to identify PIO tendencies. Furthermore, Gibson’s time domain criteria were in good agreement with pilot ratings and comments.

**SAAB**

**Report comments**

The report should be more self-contained. This means that the different criteria should be explained in such detail that an engineer should be able to implement the method without looking for details in other references. A typical example illustrating the method is also of great value.

**Experience on PIO criteria**

Currently, Saab is using 3 criteria for testing a new FCS edition for the Saab Gripen.
• Neal-Smith
• Smith-Geddes
• Gibson (phase rate, amplitude margin, and dropback)

When using the Neal-Smith criterion Saab deviates slightly from the description in Section 3.2.1. For Category C we use 3.0 rad/s bandwidth, and the pilot time delay is 0.25s. We use the old boundaries.

For Gibson's phase rate we use the limits $\frac{d\Phi}{df} > -70$ deg/Hz, frequency at -180 deg should be $\geq 1$ Hz. For the Gain-Phase template we use the gain margin 16 dB.

The criteria are evaluated for a light aircraft (20% fuel) at low altitude, for a few selected speeds, and for both the single-seater and two-seater versions.

In general, the different PIO criteria may give contradicting results for a flight condition. For example: in one particular flight condition the Neal-Smith criterion may give Level 1, while the Gibson phase rate is in Level 2. And vice versa in another flight condition.

For the latest FCS editions, the PIO criteria have mainly been checked for differences between the new edition and the previous flying edition. Since the earlier editions have been flight tested and were found to be free from PIO proneness, you can rely on similarity between the editions. If PIO criteria results for a new edition are essentially the same as for the previous flying edition, they are accepted. But if results abruptly changes into Level 3 or are much worse than before, this is taken as an alarm bell.

One other important check is the Klonk-simulations, which is a test on abrupt manoeuvring where rate limiting takes place. If the simulations stay inside a defined angle-of-attack envelope, we conclude that even if the pilot gets into a PIO this will not cause loss of control of the aircraft.

Looking back into the early design stages of the Gripen FCS, a number of PIO criteria have always been used in order to check that the basic design is reasonably good with respect to PIO.

After the Stockholm Water Festival crash (August 1993) around 10 PIO criteria were used in order to evaluate the PIO proneness of the unfortunate FCS edition. The results were OK for all the used criteria, since they were all linear criteria. This indicates the need for nonlinear PIO criteria in order to catch PIO caused by rate limiting.
References


