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Technical and Psychological Aspects of Pilot Gain

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Technical and Psychological Aspects of Pilot Gain

Semesterarbeit

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Juli 2012

Eidesstattliche Erklärung

Hiermit erkläre ich, Anja Simm, gegenüber dem Lehrstuhl für Flugsystemdynamik der Technischen Universität München, dass ich die vorliegende Semesterarbeit selbstständig und ausschließlich unter Zuhilfenahme der im Literaturverzeichnis genannten Quellen angefertigt habe.

Die Arbeit wurde in gleicher oder ähnlicher Form an keiner anderen Hochschule oder Universität vorgelegt.

Garching, 31. Juli 2012

Anja Simm

Kurzfassung

Pilot Gain ist ein im Flugversuch weit verbreiteter Begriff, der einen Aspekt des manuellen Steuerverhaltens von Piloten beschreibt. Während ein Pilot für die gleiche Aufgabe sanfte und eher langsame Steuereingaben vornimmt, führt ein anderer eher hochfrequente, schnellere und insgesamt häufigere Bewegungen aus.

In der vorliegenden Arbeit werden verschiedene Aspekte von Pilot Gain untersucht: Zunächst wird in einer umfangreichen Literaturrecherche nach Definitionen von Pilot Gain gesucht sowie dem Kontext, in dem Pilot Gain verwendet wird.

Die Frage, warum verschiedene Piloten unterschiedliches Steuerverhalten aufweisen, kann nach momentanem Stand der Wissenschaft nur unzureichend geklärt werden. Einzelne psychologische Studien, die in vorliegender Arbeit aufgeführt werden, unterstützen jedoch die Theorie, dass Unterschiede in der Persönlichkeitsdimension „Extraversion“ gemäß dem Modell der „Big Five“, mit individuellen Bewegungsabläufen korrelieren.

Im letzten Teil der Arbeit werden 25 verschiedene Pilot Gain-Maße mit Hilfe von Daten einer Simulatorstudie im Hubschrauber-Simulator auf Korrelation untereinander untersucht. Dabei soll herausgefunden werden, ob Beziehungen zwischen ihnen erkennbar sind. Eine klare Aufteilung in zwei Gruppen von Maßen ist erkennbar, die untereinander korrelieren. Ein Vergleich mit Ergebnissen einer anderen Simulatorstudie zeigt, dass der Kontext, in dem Messdaten aufgenommen werden, eine große Rolle spielt.

Abstract

The term “pilot gain” plays a central role in flight tests and describes an aspect of how the pilot acts on the inceptor when controlling an aircraft. While one pilot may exert smooth and rather slow control inputs, another pilot might force the stick very hard and exert fast and high-frequency inputs for the same task.

The present thesis investigates several aspects of pilot gain: At first, an extensive literature research is performed to investigate definitions of pilot gain as well as the context, pilot gain is utilized in.

The question why different pilots use different types of control behavior can only be explained unsatisfactorily with respect to the momentary state of science. However, a selection of psychological studies which are included in the present thesis, support the theory that differences in the personality dimension “extraversion” of the “Big Five” model correlates with differences in body movements.

In the final part of the thesis, the correlation among 25 different pilot gain measures is calculated on the basis of data from a helicopter simulator study. The objective is to find out whether relations between them exist. A clear division into two groups of measures that correlate with each other can be detected. A comparison with results from another simulator study shows that the context in which the measurement data is taken, plays a major role.

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List of Abbreviations

Abbreviation	Description
AC	Attitude Command
DLR	Deutsches Zentrum für Luft- und Raumfahrt
DTT	Discrete Tracking Task
FHS	Fliegender Hubschrauber Simulator
MT	Movement Time
NASA	National Aeronautics and Space Administration
EPQ	Eysenck Personality Questionnaire
PIO	Pilot Involved Oscillations / Pilot Induced Oscillations
PSD	Power Spectral Density
RC	Rate Command
RT	Reaction Time
RMS	Root Mean Square
SOS	Sum of Sine

1 Introduction

Loosely speaking, pilot gain describes the individual aggressiveness with which a pilot controls his aircraft. Although this concept plays a central role in flight test and is well understood intuitively, mathematically it is not defined precisely.

The thesis presented aims to investigate three major questions concerning pilot gain, which are each represented by one chapter:

- In which context and under which definitions can pilot gain be found in literature?
- In a psychological and physiological context, what could explain individual differences in pilot?
- How do possible measures of pilot gain correlate?

During the investigation the procedure for the respective objective was as follows:

Chapter 2 - literature review:

The objective of this chapter is to create an overview of how the term pilot gain is used in literature and whether definitions can be found. Moreover synonyms that are likely to be used for pilot gain are differentiated. Every element in the table of bibliographical references was checked and the relevance evaluated. The most important results are summarized in chapter 2.

Chapter 3 - psychological and physiological aspects of pilot gain:

The objective of this chapter is to give some ideas of how psychological and physiological aspects could be reasons for the individual pilot gain which can be observed in practise. The most important results of the interdisciplinary research with experts and literature research are summarized in chapter 3.

Chapter 4 - measures of pilot gain:

The objective of this chapter is to figure out whether any dependencies between possible pilot gain measures can be detected on the basis of test data of a simulator study.

2 Literature Review

The term “pilot gain” describes the way the pilot acts on the inceptor during flight. There is no generally accepted verbal or mathematical definition of pilot gain and often other terms are used in literature to describe the phenomenon [Nie11] .

The literature review aims to find out whether literature offers definitions of pilot gain and synonyms used, as well as to figure out in which context these terms can be found.

The following chapters provide, in addition to a summary of the most important results, a table listing all bibliographical references that were checked (chapter 2.3). All indicated references within this chapter refer to this table.

2.1 Synonyms Used for Pilot Gain

Five exemplary synonyms which are likely to be used for pilot gain are described and differentiated from each other, as well as differentiated from pilot gain as used in this thesis.

Pilot Workload

Cooper and Harper [27] define pilot workload as physical and mental effort required to perform a specified piloting task. This definition describes workload as the effort which needs to be done. Other definitions concentrate on workload as activities done by a crew [43] that also include e.g. communication, navigation or crew management.

Thus, workload can be meant as a number of tasks as well as as a measure the amount of stress the same task causes the individual. Gartner and Murphy [43] as well as Verwey [115] have assembled various definitions of workload which can be found in literature.

A lot of literature investigates ways to decrease workload (especially for airline pilots) and several physiological measures for workload heart rate and respiratory rate [103] can be found. A pilot’s correct performance in the cockpit being very safety relevant explains the amount of research which was done in this field.

Bauschat, Gestwa and Leßling [15] specify two established methods to estimate the subjective workload impression: NASA-Task Load Index and the (modified) Cooper Harper Rating Scale (also see chapter 4.2.3).

With increasing workload the operator is more and more occupied with a task until the operator’s human limitations are reached and he cannot accomplish the task anymore. When using the term workload within the meaning of pilot gain, this is where you find a certain discrepancy: as an example, a high pilot gain does not necessarily reflect that the pilot’s workload is high. There are experienced pilots who naturally fly with high gain without being close to their limit. Those would have a higher mental workload if they had to perform a task intentionally low gain [95].

2.1.1 Pilot Control Activity

One can easily imagine an increasing control activity by the pilot associated with increasing workload. It can be construed that pilot control activity is also used as a measure for workload [36].

Though an increasing workload possibly makes the operator increase his control activity, it does not necessarily mean that high control activity is caused by high workload.

There are several measures to assess control activity [16] [36]. Field and Giese [16] enlist four general possibilities: the Root Mean Square (RMS) of input amplitude to represent the average input magnitude during a specified segment of piloted control, Power Spectral Density (PSD - frequency distribution of pilot inputs), number of Control Reversals (triggered when the control reverses its direction of movement) and Aircraft Energy (energy in the response of the aircraft that results from the control input).

The concept of pilot control activity is closely related to pilot gain [95].

Also in other fields, for example automotive engineering, high values of steering wheel reversal rate (SRR) are indicative of high driving task demand [72]. For example Krajewski et al. [72] investigated a fatigue monitoring system for vehicle drivers. In their case, the expected fatigue-induced changes in steering behaviour typically are a pattern of slow drifting and fast corrective counter steering.

2.1.2 Pilot Inceptor Workload

Gray [49] suggests the term “pilot inceptor workload” as measure for pilot gain. It is defined as a combination of the independent variables “duty cycle" and “aggressiveness" [51]:

Duty Cycle: When a pilot is involved in a tracking task, he is unlikely to be constantly moving the controls. He occasionally stops changing the position of the control, for example in order to allow the aircraft to respond by itself. Duty cycle is the percentage of time the pilot is changing his input on the stick, whether through force or position, thus stick speed is not equal to zero. In terms of pilot inceptor workload, when duty cycle is increased, pilot inceptor workload is increased as well [51].

Aggressiveness: When the pilot is moving the inceptor, the movement can be characterized as effort the pilot is putting into the motion (displacement change times the force applied)[51].

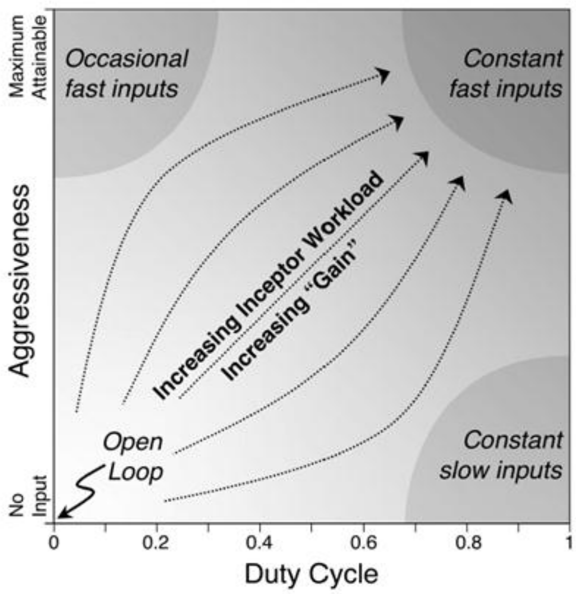

Figure 2-1: Pilot Inceptor Workload [51]

Figure 2-1 indicates the two-dimensional picture of Pilot Inceptor Workload: As the measured inceptor workload for a given task moves away from the origin, it can be said that the pilot's inceptor workload is increasing. Hypothetically, this should correspond to increasing pilot gain. The proportion of duty cycle to aggressiveness can also express something about the aircraft.

Thus, the pilot inceptor workload may be used to show the change in pilot inceptor workload or "gain", and be used to compare the workload between different pilots and different attempts at the same task [51].

Although pilot inceptor workload hits the mark quite well there is still a discrepancy: high inceptor workload can also result from inexperience or low flying skills which would reflect high physical and mental workload. But in reality there are experienced pilots who naturally fly with high gain without being close to their limit [95].

2.1.3 Aggressiveness

"Aggressiveness" is another term typically associated with pilot gain. In a survey among people from the flight test environment being familiar with pilot gain Niewind [95] found that nearly all of them used the term "aggressiveness" to explain pilot gain.

As already described in chapter 2.1.2, Gray uses this term as one of the two dimensions of pilot inceptor workload.

In psychology, aggressiveness is defined as a behaviour intending to harm an individual in a direct or indirect way [31]. The increase then is destruction. Literature concerning aggressive behaviour mostly deals with children or young adolescents and their social background as possible reason for this kind of behavior. When you look for something other than animate beings, e.g. music or sports, the first associations would be fast, alert and strong.

Concerning pilot gain, there are several examples in literature for aggressive manoeuvres or aggressive tracking when talking about high pilot gain, for instance [5] [55] [68]. A too high gain will reduce the stability of the control loop [5]. Often a connection between aggressive manoeuvres and Pilot Induced Oscillations (PIO) is made: In many cases aggressive pilot inputs are referred to as reason to bring out unstable states of an aircraft and PIO.

Though this is a way to combine pilot gain with aggressiveness, most of the time aggressiveness is associated with violence and therefore appraised as bad behavior whereas high or low pilot gain are of the same value and not related to good or bad performance.

2.1.4 Abruptness

Contrary to “aggressiveness”, “abruptness” seems to be a less judgmental term. With low gain being characterised as “smooth” or “relaxed”, “abrupt” manoeuvring could be associated with high gain. This would be in line with “agricultural”, “rough” and “ham-fisted”, terms associated with high gain among people from the flight test environment [95] (also see chapter 2.2.4).

As already mentioned before, high gain is often referred to as evoking PIO. MIL-HDBK-1797A [8] provides a PIO tendency classification as flow-chart including a request, whether abrupt manoeuvres initiated by the pilot cause oscillations.

2.2 Pilot Gain in Literature

While the last chapter concentrated on terms used in literature when talking about pilot gain, the following subchapters describe the context, the actual term “pilot gain” is used in.

2.2.1 Pilot Gain in Control Theory

Many attempts have been made to simulate pilot behaviour in a closed loop control. To do so, human control behaviour has to be expressed by means of mathematical models. One of these models often referred to was published by Neal and Smith in 1971 [93]. The closed-loop transfer function is shown by equation (2-1):

$$F(s) = K_p e^{-T_e s} \frac{T_D s + 1}{T_I s + 1} \qquad \textbf{(2-1)}$$

K_p represents the pilot (model) gain, T_e represents the central processing delay, T_D and T_I the lead and lag compensation. Variations of these parameters reflect the pilot adapting to particular task configurations.

The proportional element/gain factor K is referred to as pilot gain in a large amount of papers and therein mostly listed in a list of abbreviations as for example K, K_p, K_{pil}, K_e. In [93] the parameter K_{BW} is introduced as Pilot Gain at the frequency which the pilot is trying to achieve in precision tracking tasks.

In other cases the term "pilot model gain" is used to define K when talking about control theory and pilot models [97] [119]. The term "pilot model gain" avoids confusion as it unmistakably means the gain factor for a simulated pilot, not a "real" human pilot's gain. Celere, Maciel and Varoto [26] use the term "human pilot gain" to draw a clear distinction.

This distinction is important since - whereas you can set discrete values for a gain factor within a simulation - the parameter is hardly tangible for a human pilot [95] and as driven by a combination of experience, acclimation, desire, error tolerance, and stress, is a lot more complex [52]. According to Gray [51] there probably is not any parameter in a pilot's brain which could be directly translated as "gain".

Still one can find the term "pilot gain" used for both cases – as "human" pilot gain as well as as pilot model gain - within the same paper, for example [2]

2.2.2 Pilot Induced Oscillations (PIO)

Notably, literature including information about pilot gain discusses pilot induced oscillation. Pilot induced oscillations (PIO) are defined as inadvertent, unwanted aircraft attitude and flight path motions which originate from anomalous interactions between the aircraft and pilot.

PIO tendency is an indication of a handling qualities deficiency and usually only occurs when the pilot attempts tight closed-loop control of the aircraft, such as during fine tracking [113]. Hanley [55] also mentions that the pilot must aggressively manoeuvre the aircraft for PIO to occur. Once the PIO has started to occur, according to [5] the pilot can stop the PIO by reducing his gain. To make sure that the potential of PIO tendencies is minimal, an airplane must be evaluated by test pilots conducting high-gain (wide-bandwidth) tasks [6].

With MIL-HDBK-1797 [8] describing how to bring out PIO, the term "bandwidth" is also used as synonym for the pilot's aggressiveness. Varying the bandwidth of a pilot model in a simulation simulates more aggressive or relaxed pilot behaviour [111]. Bandwidth seems to be a term often associated with, when describing different pilot gains.

2.2.3 High Gain and Low Gain Tasks

Pilot gain is often mentioned in connection with high gain or low gain tasks. PIO is associated with high pilot gain. There are several high gain tasks which are typically mentioned to evoke PIOs: Aerial Refueling, Formation Flying, Precision Tracking, Precision Approaches and Spot Landings (e.g., carrier approach), Terrain Following, Demanding/Unexpected Transitions [87]. Precise control, prompt reactions and striving for small error tolerance are characteristic.

In contrast, typical low gain tasks are calm, demand few corrections and small amplitudes. ILS approaches are an example for low gain tasks [15].

2.2.4 Associations with High Gain and Low Gain

High gain is associated with closed-loop, aggressive, urgent and precise pilot control behaviour [9], tracking [15], even control difficulties [36], high bandwidth [51], highly interactive [86] and full-attention [87] performance. According to van der Geest, Hosman and Schuring [111], a pilot will increase his gain to improve tracking performance. However, a too high gain will reduce the stability of the control loop.

According to Hall [54] operating at high gain and exercising high gain control is when a pilot applies continuous high frequency control inputs in order to achieve a given task,. Operating at low gain and exercising low gain control is when a pilot applies a control input, and is content to wait a finite time before making a further control input, largely open loop control over his vehicle.

In other sources low gain is associated with low frequency [15], relaxed [26] open loop and gentle tracking manoeuvres, smaller inputs [36] and low bandwidth [55]. A small error is accepted in favour of a more stable pilot-vehicle system [95]. Since a lot of literature referring to pilot gain is actually dealing with PIO, it is not surprising that high gain is described more often than low gain.

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2.2.5 Pilot Gain: Intentionally Chosen or Individual?

There are sources stating that low or high gain is something which is conducted, as well as there are sources declaring low or high gain being something intentionally chosen and something individual: each pilot has his/her own way of responding to the same flight condition.

Without using the term pilot gain, Kaewchay and Dogan [65] state that in order to achieve precise tracking of a reference flight attitude, while one pilot may exert smooth control inputs by moving the stick gently, another pilot might force the stick very hard to accomplish the same specific task. This depends on the personality, skill, knowledge based on training and experience of each pilot.

Pilots can then be categorized as rather high or low gain pilot [119] or high or low gainers [95] without judging the control strategy and dividing up into bad or good.

2.2.6 Pilot Gain in Other Disciplines

Apart from aviation, gain can also be found in a similar meaning, sometimes as pilot gain, pilot's gain, operator's, controller's or driver's gain.

Models of driver steering control in regulation tasks are well established and were used in a number of studies of driver/vehicle response and performance. They are typically expressed in Laplace transform (transfer function) or differential equation form, in a classical control theory manner. Simple form of the driver control models are based on the crossover model of the human operator (McRuer) [122]. Also in driving models, K can be found as symbol for the gain factor of the driver model.

In [114] K, the gain factor in a driver model was modified to involve a dependence on vehicle speed and frontal visibility. Moreover two constant parameters C_1 and C_2, included in the formula defining K, represent the physiological and psychological state of the driver.

2.3 Table of Bibliographical References

The following chapter provides a table listing all bibliographical references checked in alphabetical order.

The table's fourth column offers a rating in each case of how relevant ("rel").the source is regarding the question (1 to 5, 5 being the most relevant). Afterwards the expression used is listed as well as "YES" or "NO" depending on whether a definition is given or not. Moreover the last column includes quotations in black writing and comments in violet.

#	author	title	Rel	expression	Def?	content/quotations/comments
1	Amato, Iervolino, Scala, Verde [Ama99]	*Actuator Design for Aircraft Robustness Versus Category II PIO*	3	Pilot Gain	**YES**	"increase of the pilot gain"; "pilot gain Kp" gain factor in control theory; "full attention manoeuvres […] require an high pilot gain" high-gain task;
2	Amato, Iervolino, Pandit, Scala, Verde [Ama00]	*Analysis of Pilot-in-the-Loop Oscillations Due to Position and Rate Saturations*	3	Pilot Gain	**YES**	"pilot gain KP" gain factor in control theory; "It is indeed assumed that the pilot would try to control the aircraft with such a range of gains"; mix-up pilot gain/pilot model gain; "the range of pilot gains for which the phase margin of the loop transfer function is in the interval from 70° (lower pilot gain) to 20° (higher pilot gain)";
3	Ananthkrishna [Ana04]	*Small-Perturbation Analysis of Airplane Flight Dynamics - A Reappraisal.I Longitudinal Modes*	1	-	**NO**	-
4	Anderson, Page [And95]	*Unified Pilot-Induced Oscillation Theory*	2	Pilot Gain	**YES**	"K Pilot Gain" gain factor in control theory;
5	Anon [Res00]	*Flight Control Design – Best Practices*	5	Pilot Gain	**NO**	"pilot command gains that are too high"; "combination of very high pilot gain and the control system"; "Once away from the ground, pilot gain decreased and the PIO stopped." Pilot Gain/PIO; "Modifications to reduce the pilot command gain" ; "The use of high gain tracking tasks, such as air-to air tracking of a manoeuvring target [...] enhanced the designer's ability to drive the pilot's gain up under operationally significant scenarios."; "the pilot can stop the PIO by reducing his gain";

#	author	title	Rel	expression	Def?	content/quotations/comments
5	Anon [Res00]	*Flight Control Design – Best Practices*	5	Pilot Gain	**NO**	"It is assumed that the human pilot is not able to adapt his control behaviour (e.g. pilot gain) to the new dynamic characteristics (e.g. non-linear aircraft) immediately" depending on the individual!; "Increasing pilot gain Kp" gain factor; "It is recommended that a gain spectrum from Phi_cr=-120 (low pilot gain) up to Phi_cr=-160 (high pilot gain) should be applied. This gain spectrum should be used to assess the sensitivity of the aircraft to the pilot model gain." measure for Pilot Gain;
				Workload	**NO**	"help reduce pilot workload"; "pilot compensation angle (the indicator of pilot workload)."
				Aggressiveness	**NO**	"overly aggressive pilot inputs to uncover problem areas."; "But, it also has some potential to explain the PIO during landing, since this configuration is extremely sensitive to bandwidth, which means aggressiveness of the pilot"; "changes in the aggressiveness of the task performance and the speed of the closed-loop response."
6	Anon [Con98]	*Flight Test Guide For Certification Of Transport Category Airplanes*	4	Pilot Gain	**NO**	"the airplane must be evaluated by test pilots conducting high-gain (wide-bandwidth), closed-loop tasks to determine that the potential of encountering adverse A-PC tendencies is minimal";

#	author	title	Rel	expression	Def?	content/quotations/comments
6	Anon [Con98]	*Flight Test Guide For Certification Of Transport Category Airplanes*	4	Pilot Gain	**NO**	"The tasks are used only to increase the pilot's gain, which is a prerequisite for exposing A-PC tendencies"; "keep the test pilot's gain high [...] while accomplishing the task."
7	Anon [Web01]	*Flying Qualities Flight Testing of Digital Flight Control Systems*	3	High-Gain	**NO**	"The key to success is to eliminate motion, minimize visual-time delays and conduct a sufficiently high-gain task"; "A high-gain, zero error, random tracking task such as handling qualities during tracking"
8	Anon [Dep97]	*MIL-HDBK-1797 - Flying Qualities of Piloted Aircraft*	3	Pilot Gain	**YES**	"With such systems a small increase in pilot gain results in a large change in crossover frequency and a corresponding rapid decrease in phase margin" ; gain factor in control theory;
9	Anon [Fil02]	*PIO Handbook*	3	Aggressiveness, Pilot Gain	**YES**	"Kpil = pilot gain" gain factor in control theory; "Because the PVS is a central component in severe PIOs, the criterion must relate to closed-loop, high-gain, aggressive, urgent and precise piloted-control behaviour."; "The acquisition time D was a measure of task aggressiveness and when assuming a perfect compensator, D can be related to an equivalent bandwidth through:"; "Variations of the acquisition time corresponds to changes in the aggressiveness of the task performance and the speed of the closed-loop response."; "evaluation of the pilot’s control activity.";

#	author	title	Rel	expression	Def?	content/quotations/comments
9	Anon [Fil02]	*PIO Handbook*	3	Aggressiveness, Pilot Gain	**YES**	"It is recommended that a gain spectrum from Φ = −120° cr (low pilot gain) up to Φ = −160° cr (high pilot gain) should be applied."
10	Arencibia, Mitchell, Muñoz [Mit04]	*Real-Time Detection of Pilot-Induced Oscillations*	3	High-Gain	**NO**	"It is very common for oscillatory behavior to appear in time responses, especially during periods of high-gain, closed-loop pilot activity." detecting/measuring PIO
11	Ashkenas et al. [Ash64]	*Pilot-Induced Oscillations their cause and analysis*	3	Pilot Gain	**NO**	"Pilot trainees or test pilots feeling out a new aircraft often tighten up on their control response enough to provide one or two oscillations indicating incipient instability. If this tendency is easy to avoid, and if a modest reduction in pilot gain (e.g., 25 to 50 percent) can remove the instability, then such situations do not usually end up as serious PIO cases"; "If the analyses show that no equalization is needed by the pilot prior to a PIO, but that the requi-ed pilot gain is very low (i.e., control is very sensitive), then incomplete pilot gain adjustment may well cause PIO tendencies" "Not until the pilot's gain is raised about 8 db [...]"; "the difference in tolerable pilot gain for instability due to bobweight effects is negligible"
12	Barnes [Bar69]	*A Simulator Investigation of Rolling Requirements for Landing Approach*	1	-	**NO**	-

#	author	title	Rel	expression	Def?	content/quotations/comments
13	Barrows, Powell [Bar00]	*Flying a Tunnel-in-the-Sky Display within the Current Airspace System*	2	Workload	**NO**	"Starting this descent requires an aircraft configuration change in power and pitch accompanied by pilot workload"; "The increased (and unnecessary) workload associated with pitch and power changes" increasing workload caused by additional tasks; "Eliminating unnecessary aircraft configuration changes reduced the inherent workload."; The Tunnel-in-the-Sky display allowed[...] while reducing subjective pilot workload;
14	Basappa, Raol, Singh [Sin05]	*Modeling and Parameter Estimation for a Fly-by-Wire Aircraft*	1	-	**NO**	-
15	Bauschat, Gestwa, Leißling [Asc04]	*A Score Monitoring System to Support Evaluation Pilots in Flight*	4	High-Gain, Workload	**YES**	"precision/low gain and precision/high-gain tasks"; "low frequency, low gain tasks like ILS approaches […] and aggressive high gain tracking tasks, where the evaluation pilot has to follow given command sequences in the pitch or the roll axes"; Workload: 1) NASA Task Load Index (NASA TLX); 2) Cooper-Harper-Rating
16	Belyavin, Nguyen, Robel, Woodward, Woolworth [Bel05]	*Development of a Novel Model of Pilot Control Behavior in Balked Landings*	3	Control Activity	**NO**	"The pilot model calibration procedure was designed to choose parameter values that minimized the objective function, selected to reflect pilot control behavior, for a specific pilot/condition combination."; "Frequency bands for spectral analysis of control movements" bandwidth;

#	author	title	Rel	expression	Def?	content/quotations/comments
16	Belyavin, Nguyen, Robel, Woodward, Woolworth [Bel05]	*Development of a Novel Model of Pilot Control Behavior in Balked Landings*	3	Control Activity	**NO**	"Control activity was calculated as the mean squared deviation of control position from the mean and the contribution to the objective function was calculated as the square of the difference between the logarithm of observed control activity and the logarithm of modeled control activity."
17	Belyavin, van den Berg, Hoermann, Hosman, Peixoto, Rager [Bel051]	*Analysis of Pilot Control Behavior During Balked Landing Maneuvers*	1	-	**NO**	Pilots' response time/Pilot Model
18	Berntsen, Mulder, van Paassen [Ber05]	*Modelling Human Visual Perception and Control of the Direction of Self-Motion*	2	Pilot Gain	**YES**	"Kp the pilot gain, a dimensionless parameter" gain factor in control theory;
19	Bezdek, Mays, Powell [Bez04]	*The History and Future of Military Flight Simulators*	1	-	**NO**	-
20	Bisgood [Bis67]	*A Review of Recent Research on Handling Qualities, and its Application to the Handling Problems of Large Aircraft part 1-2*	2	Pilot Gain	**YES**	"the pilot's gain, Kp," gain factor in control theory;
21	Bisgood [Bis70]	*A Review of Recent Research on Handling Qualities, and its Application to the Handling Problems of Large Aircraft part 3*	1	-	**NO**	-
22	Brown [Bro041]	*AIRS II Flight Determination of Turboprop Transport Aeroplane Lift, Drag, and Propulsive Effiency Effects in Freezing Drizzle Icing*	1	-	**NO**	-

#	author	title	Rel	expression	Def?	content/quotations/comments
23	Brown, Craig, Dillon, Erdos [Bro042]	*Flight Manoeuvre and Spin Characteristics of the Harvard 4: Application to Human Factors Flight Research*	1	-	**NO**	-
24	Campos, Hansen, Murray [Han04]	*The NASA Dryden AAR Project: A Flight Test Approach to an Aerial Refueling System*	3	Workload	**NO**	"This technique, called static mapping, required considerable flight time and high pilot workload" typical high-gain task; "Performing precision research maneuvers in the vicinity of the drogue resulted in high workload for the receiver pilot."
25	Carlsson [Car04]	*Design and Testing of Flexible Aircraft Structures*	1	-	**NO**	-
26	Celere, Maciel, Varoto [Cel07]	*Verifying Pilot Gain in PIO Flight Test*	5	Pilot Gain	**YES**	"high gain (demanding) task;" "A literature review showed no established metric to evaluate how high was the gain employed during the maneuver, so a method is offered to identify poorly executed (with low pilot gain) synthetic task PIO flight tests." "Test #02 was performed with high pilot gain, the same way as test #01. However, test #03 was performed opposite: the task was very easy to follow and the pilot was instructed to use very low gain and to pilot in a “relaxed way"; measuring the human pilot gain;
27	Cooper, Harper [Coo69]	*The Use of Pilot Rating in the Evaluation of Aircraft Handling Qualities*	3	-	**NO**	Handling Qualities Rating Scale

#	author	title	Rel	expression	Def?	content/quotations/comments
28	Cox, Jackson [Cox97]	*Evaluation of High-Speed Civil Transport Handling Qualities Criteria With Supersonic Flight Data*	1	-	**NO**	-
29	Day [Day97]	*Coupling Dynamics in Aircraft: A Historical Perspective*	1	-	**NO**	-
30	de Mello, de Soviero [DeM04]	*A Simplified Conceptual Design High-Lift Methodology for Transport Aircraft*	1	-	**NO**	-
31	Dietrich, Walter [Die72]	*Grundbegriffe der psychologischen Fachsprache*	4	Aggressiveness	**YES**	"Aggression ist die Bezeichnung für jene Verhaltensweise, mit denen die direkte oder indirekte Schädigung eines Individuums, meistens eines Artgenossen, intendiert wird. Als Steigerungsform der Aggression kann die Destruktion angesehen werden; Aggression ist auf Schädigung, Unterdrückung oder Ablehnung der Eigentätigkeit oder Eigenart des anderen, Destruktion auf Vernichtung und Zertrümmerung gerichtet."
32	Dotter [Dot00]	*An Analysis of Aircraft Handling Quality Data Obtained from Boundary Avoidance Tracking Flight Test Techniques*	2	-	**NO**	-
33	Duda [Dud95]	*Effects of Rate Limiting Elements in Flight Control Systems- A New PIO Criterion*	3	Pilot Gain	**YES**	pilot model
34	Field [Fie94]	*A Piloted Simulation Investigation of Several Command Concepts for Transport Aircraft in the Approach and Landing*	4	Pilot Gain	**NO**	"A high workload, low gain sampling technique was used to avoid PIOs and achieve what was desired"; "PIO prone, could lose control if pilot gain gets too high." high gain evoking PIO;

#	author	title	Rel	expression	Def?	content/quotations/comments
34	Field [Fie94]	*A Piloted Simulation Investigation of Several Command Concepts for Transport Aircraft in the Approach and Landing*	4	Pilot Gain	**NO**	"The additional visual cues and real life anxiety are required to get the required pilot gain.";
35	Field [Fie93]	*The Application of a C* Flight Control Law to Large Civil Transport Aircraft*	1	-	**NO**	-
36	Field, Giese [Fie05]	*Appraisal of Several Pilot Control Activity Measures*	4	High-Gain, Control Activity, Pilot Gain	**NO**	"Various measures of pilot control activity have been used to gain an understanding of pilot control technique and workload" "[...] 2.0 – 4.0 rad/s: Higher-gain closed-loop control associated with increased task urgency or handling issues with the aircraft, such as a PIO. 4.0 – 10.0 rad/s: Very high-gain closed-loop control, almost certainly associated with control difficulties." "While the offset correction, flare and touchdown is considered a high-gain task"; "Differences between pilot technique are also evident in the PSDs. Pilot A and C [...], using smaller inputs in the VMS than pilot B, especially at low frequency. [...] This observation correlates with his reputation as a low-gain pilot. At higher frequencies, the pilots look more similar, with their technique seeming to be a greater function of additional time delay and evaluation environment." individual pilot gain;

#	author	title	Rel	expression	Def?	content/quotations/comments
37	Field, Pinney, van Paassen, Stroosma, Rivers [Eff04]	*Effects of Implementation Variations on the Results of Piloted Simulator Handling Qualities Evaluations*	4	Pilot Gain	**NO**	"command gain" Sensitivy of stick; "The most probable cause of pilot B using such small inputs in the SRS is due to him adopting a different control strategy over the ten-year interval since the earlier TIFS and VMS experiments."; "Historically a low-gain pilot, it is hypothesized that as his experience with commercial transport aircraft has increased, his control technique has developed over the years." individual;
38	Field, van Paassen, Salchak, Stroosma [Fie04]	*Validation of Simulation Models for Piloted Handling Qualities Evaluations*	1	-	**NO**	-
39	Field, von Klein, van der Weerd, Bennani [Fie00]	*The Prediction and Suppression of PIO Susceptibility of a Large Transport Aircraft*	3	Pilot Gain	**YES**	"PIO tendency […] usually only occurs when the pilot attempts tight closed-loop control of the aircraft, such as during fine tracking, aerial refuelling or landing tasks"; "Pilot Model Parameters are K_pil (pilot gain)"
40	Foster, Wilborn [Wil04]	*Defining Commercial Transport Loss-of-Control: A Quantitative Approach*	1	-	**NO**	-
41	Friehmelt, Raab, Spangenberg [Fri05]	*Simulation Examples of Military Transport Issues in Research Simulator*	3	High-Gain	**NO**	To develop new handling qualities criteria, a high-gain tracking tasks ahs been included in the simulator functions; tracking as high-gain task;
42	Gadient, Weltz [Gad04]	*Adaptive / Reconfigurable Flight Control Augmentation Design Applied to High-Winged Transport Aircraft*	1	-	**NO**	"Gain" as component in Control Theory

#	author	title	Rel	expression	Def?	content/quotations/comments
43	Gartner, Murphy [Gar79]	*Concepts of Workload*	4	Workload	**YES**	"pilot workload refers to how much a pilot must do to perform a specified flight operation"; "Jahns (1) has found it useful to characterize workload as "an integrative concept for evaluating the effects on the human operator associated with multiple stresses occuring within man-machine environments." "Cooper/Harper (5) "The term workload is intended to convey the amount of effort and attention, both physical and mental that the pilot must provide to attain a given level of performance"; "total activity done by the crew to do tasks (also communication, navigation,...)
44	Gautrey [Gau96]	*Flight Control System Architecture Analysis and Design for a Fly-by-Wire Generic Regional Aircraft*	1	-	**NO**	-
45	Ghidella, Mosterman [Ghi05]	*Requirements-Based Testing in Aircraft Control Design*	1	-	**NO**	-
46	Gibson [Cam99]	*Development of a Methodology for Excellence in Handling Qualities Design for Fly-by-wire Aircraft*	2	Pilot Gain	**YES**	"pilot gain Kp" gain factor in control theory;
47	Gilbreath [Gil01]	*Prediction of Pilot-Induced Oscillations (PIO) due to Actuator Rate Limiting Using the Open-Loop Onset Point (OLOP) Criterion*	2	Pilot Gain	**YES**	"Kg Pilot Gain"; gain factor in control theory "PIOs often occur during high gain events requiring tight control by the pilot; such as takeoff, landing, aerial refueling, and formation flying" gain applied by human pilot; "evaluate pilot gain sensitivity."

#	author	title	Rel	expression	Def?	content/quotations/comments
47	Gilbreath [Gil01]	*Prediction of Pilot-Induced Oscillations (PIO) due to Actuator Rate Limiting Using the Open-Loop Onset Point (OLOP) Criterion*	2	Pilot Gain	**YES**	"The lower magnitude (-90°) of the ranges will be referred to as low gain pilots and the upper (-130°) as high gain pilots for this longitudinal analysis"
48	Grant, Hosman, Schroeder [Hos05]	*Pre and Post Pilot Model Analysis Compared to Experimental Simulator Results*	1	-	**NO**	-
49	Gray [Gra05]	*Boundary-Avoidance Tracking: A New Pilot Tracking Model*	5	Pilot Gain	**NO**	"it was found that treating the pilot gain as a function of the time to exceeding a given boundary can result in the type of control inputs typical of pilots in such situations, including the worst types of pilot-induced oscillations"; "ascribing the oscillation to extraordinarily high pilot gains while the pilot is attempting to control a certain parameter. But these explanations did not correspond to the pilots' actual experience." "PIO caused by high gain tracking of a single parameter"; "The most difficult problem was identifying the source of pilot gain during boundary tracking.";
50	Gray [Gra07]	*A Boundary Avoidance Tracking Flight Test Technique for Performance and Workload Assessment*	5	-	**-**	-
51	Gray [Gra09]	*Handling Qualities Evaluation at the USAF Test Pilot School*	5	Pilot Gain	**YES**	"(US Air Force Flight Test Center, Flying Qualities Testing,): Phases I and II"; "When discussing the pilot in a closed-loop system, "pilot gain" is an analogy."

#	author	title	Rel	expression	Def?	content/quotations/comments
51	Gray [Gra09]	*Handling Qualities Evaluation at the USAF Test Pilot School*	5	Pilot Gain	**YES**	"When attempting to measure pilot gain, it is important to recognize that there probably isn't any parameter in a pilot's brain that could be directly translated as "gain."; "One of the most common methods of measuring pilot gain is through bandwidth analysis. By taking the pilot's control force inputs and plotting them as a power-spectral density (PSD) against frequency one can measure the frequency bandwidth of the pilot's inputs"; "it can be said that the pilot's workload is increa-sing. Hypothetically, this should correspond to increasing pilot gain"; "pilot gain as the mathematical entity Kp,"
52	Gray [Gra04]	*Boundary-Escape tracking A New Conception of Hazardous PIO United States Evaluation Technical Report*	5	Pilot Gain	**NO**	"If the pilot's gains are high enough, the entire system is unstable and in severe jeopardy."; "PIO' Pilot involvement in PIOs [...]. Pilot gain defines the position of the pilot on this continuum."; "Where a pilot can usually selflimit gain during point tracking and boundary avoidance, a pilot cannot generally self-limit gain during boundary escape."; "As with the point-tracking task, pilot gain is limited by the pilot's comfort."; "During point tracking, pilot gain is driven by a combination of experience, acclimation, desire, error tolerance, and stress. If the pilot gain is driven sufficiently high, a PIO may result";

#	author	title	Rel	expression	Def?	content/quotations/comments
52	Gray [Gra04]	*Boundary-Escape tracking A New Conception of Hazardous PIO United States Evaluation Technical Report*	5	Pilot Gain	**NO**	"Short-term PIOs, excited by high pilot gain and easily exited without hazard"; "several simulated strafing runs are accomplished late in this sortie to examine high-gain fixed-gunsight tracking but the student was clearly not being challenged by the task." ; "Pilot use of PIO as an indicator of excessive gain [...] is the subject of ongoing research at the USAF Test Pilot School."; PIO!;
53	Hall, Biedron, Ball, Bogue, Chung, Green, Grismer, Brooks, Chambers [Hal05]	*Computational Methods for Stability and Control (COMSAC): The Time Has Come*	1	-	**NO**	-
54	Hall [Hal89]	*The Need For Platform Motion in Modern Piloted Flight Training Simulators*	4	Pilot Gain	**YES**	"when a pilot makes a control input, and is content to wait a finite time before making a further control input, then he is said to be operating at low gain and exercising low gain, largely open loop control over his vehicle." describtion low gain; " When making continuous high frequency control inputs in order to achieve a given task the pilot is said to be operating at high gain and exercising high gain, closed loop control over his vehicle." describtion high gain; "As the manoeuvre task requirement becomes more demanding, and pilot gain increases [...]";

#	author	title	Rel	expression	Def?	content/quotations/comments
54	Hall [Hal89]	*The Need For Platform Motion in Modern Piloted Flight Training Simulators*	4	Pilot Gain	**YES**	"when flying high gain tasks, including precise tracking and air-to-air refuelling, suggest that control at high frequencies can also become important for stable vehicles and that these tasks also require motion cueing. […] stability of the total pilot/aircraft control loop will be reduced as the pilot's gain increases." "It is not acceptable when either an appreciation of the handling qualitlis of the vehicle or tasks involving high pilot gain, closed loop control are any part of the training role of the device."
55	Hanley [Han03]	*A Comparison of Nonlinear Algorithms to Prevent Pilot-Induced Oscillations Caused by Actuator Rate Limiting*	4	Aggressiveness, Pilot Gain	**NO**	"For PIO to occur, the pilot must aggressively maneuver the aircraft during a precision tracking task." "The Phase 1 investigation consisted of open loop and gentle tracking maneuvers to evaluate low (pilot) gain, low bandwidth handling qualities."; "Phase2 testing was an evaluation of high gain, high bandwidth handling qualities" bandwidth; "Pilot gain and frequency of inputs were increased during the task to evaluate PIO tendencies." here: control theory;
56	Harper, Cooper [Har84]	*Handling Qualities and Pilot Evaluation*	3	-	**NO**	-
57	Heffley [Hef82]	*pilot models for discrete maneuvres*	2	Pilot Gain	**YES**	several forms of pilot's gain, control theory
58	Heffley [Hef79]	*A Compilation and Analysis of Helicopter Handling Qualities Data*	2	Pilot Gain	**YES**	"Kp Pilot gain" gain factor in control theory;

#	author	title	Rel	expression	Def?	content/quotations/comments
59	Hess [Hes04]	*Handling Qualities and Flight Safety Implications of Rudder Control Strategies and Systems in Transport Aircraft*	2	Pilot Gain	**YES**	"Obviously continuous high-gain coordination is detrimental to tracking performance and stability."; "pilot gains Kp = 1, 2, 4, and 6." gain factor in control theory;
60	Hess [Hes05]	*Certification Standards and Design Issues for Rudder Control Systems in Transport Aircraft*	4	High-Gain	**NO**	"(FAA Advisory Circular 25-7A Flight Test Guide for Certification of Transport Category Airplanes): Therefore, in order to ensure that the airplane has achieved the flying qualities required by §§ 25.143(a) and (b), the airplane must be evaluated by test pilots conducting high-gain (wide-bandwidth) closed-loop tasks to determine that the potential of encountering adverse APC tendencies is minimal."
61	Hoffman [Hof80]	*Bibliography of Supersonic Cruise Research (SCR) Program From 1977 to Mid-1980*	1	-	**NO**	-
62	Holzapfel, Sachs, Sturhan [Hol04]	*Pilot-in-the-Loop Flight Simulation - A Low-Cost Approach*	1	-	**NO**	-
63	Johnson [Joh02]	*Suppression of Pilot-Induced Oscillation (PIO)*	4	Pilot Gain	**YES**	"The bare airframe dynamics may be stable, but the excessive demands and the resulting high gains of the pilot control can drive the system unstable"; "Kp is the pilot gain"; gain factor in control theory; "especially during Phase 2, or high gain, maneuvering" "higher gains resulted in larger stick inputs."; "Configuration very sensitive to pilot gain."

#	author	title	Rel	expression	Def?	content/quotations/comments
64	Jouniaux [Jou04]	*BEA´s comments on the report entitled "An Inquiry into whether a Pilot-Induced oscillation was a factor in the crash of American Airlines Flight 587"*	4	High-Gain	**NO**	"This system remains stable simply by using the control wheel with high gain."; "the impact of pilot conditioning on the gain"
65	Kaewchay, Dogan [Kae05]	*Design of a Probabilistic Human Pilot: Application to Microburst Escape Maneuver*	4	Pilot Gain (definition of Pilot Gain without using the expression)	**YES**	"Each pilot has his/her own way of responding to the same flight condition. For example, in order to achieve precise tracking of a reference flight attitude, while one pilot may exert smooth control inputs by moving the stick gently, another pilot might force the stick very hard to accomplish the same specific task. This dependency of the closed loop system response on the pilot can be represented in the human pilot model by means of a neuromuscular dynamics system that characterizes the personality, skill, knowledge based on training and experience of each pilot." Pilot Gain!
66	Katayanagi [Kat04]	*Pilot-Induced Oscillation Analysis with Actuator Rate Limiting and Feedback Control Loop*	2	Pilot Gain	**YES**	"maximum value of the pilot input kp" gain factor in control theory;
67	Kia, Malaek [Mal04]	*Effects of Human Pilot Energy Expenditure on Pilot Evaluation of Handling Qualities*	2	Pilot Gain	**YES**	"KP = pilot gain" gain factor in control theory;
68	Mitchell, Mason, Weakley [Mit041]	*Piloted Evaluation of Degraded-Mode Handling Qualities*	4	High-Gain	**NO**	"Rather than try to replicate all possible levels of turbulence, structured tasks serve to induce a similar high-gain activity."

#	author	title	Rel	expression	Def?	content/quotations/comments
69	Klyde, Mitchell [Mit05]	*A PIO Case Study – Lessons Learned Through Analysis*	3	High-Gain, Pilot Gain	**NO**	"high gain closed-loop control scenarios such as probe-and-drogue aerial refueling" ; "The pilot gain was set to result in a PVS phase margin of 20 deg, a value typical in the higher gain tasks that are most often associated with PIO."; "Both examples use the pilot gains necessary to achieve the linear system phase margins of 20 deg"; "the pilot is attempting a relatively low gain formation flying task that at times may require more stringent closed-loop control than at others." low gain task;
70	Klyde, Mitchell [Mit042]	*Recommended Practices for Exposing Pilot-Induced Oscillations or Tendencies in the Development Process*	4	High-Gain	**NO**	"It is very common for oscillatory behavior to appear in time responses, especially during periods of high-gain, closed-loop pilot activity" "Analysis of this event indicated that the 15 deg/sec actuator rate limit on the horizontal stabilizer combined with a high gain precision landing task led to the PIO"; "The effect of the added stick delay is to reduce the gain bandwidth"; "Use high-gain maneuvers to evaluate PIO tendency in piloted simulations";
71	Klyde, Mitchell [Mit051]	*Testing for Pilot-Induced Oscillations*	4	Aggressiveness, High-Gain	**NO**	Handling Qualities Stress Test: "The task requires the pilot to "track the precision aim point as aggressively and as assiduously as possible, always striving to correct even the smallest of tracking errors as quickly as possible."

#	author	title	Rel	expression	Def?	content/quotations/comments
71	Klyde, Mitchell [Mit051]	*Testing for Pilot-Induced Oscillations*	4	Aggressiveness, High-Gain	**NO**	"The pilot is asked to begin tracking with small-amplitude, low-frequency inputs, then increase the frequency of the input at small amplitude, and finally, increase the input amplitude at high frequency."; "series of high-gain tracking tasks to force high bandwidth pilot-in-the-loop activity (YF-22)" high gain task associated with high bandwidth; "Boeing engineers used a series of both high-pilot-gain and large-amplitude tasks to evaluate changes to the control laws to minimize the potential for PIO (C17A)." High Gain Tasks;
72	Krajewski et al. [Kra09]	*Steering Wheel Behaviour based estimation of fatigue*	2	-	**NO**	Measures of Steering Behaviours
73	Lampton, Valasek [Lam05]	*Prediction of Icing Effects on the Stability and Control of Light Airplanes*	1	-	**NO**	-
74	Lan, Guan [Lan05]	*Flight Dynamic Analysis of a Turboprop Transport Airplane in Icing Accident*	1	-	**NO**	-
75	Lee, Bussolari [Lee89]	*flight simulator platform motion and air transport pilot training*	3	Control Activity, Workload	**YES**	pilot control activity as measure for pilot workload
76	Lee et al. [Lee03]	*Simulation of Pilot Control Activity during helicopter shipboard operation*	3	Control Activity, Workload	**NO**	watch control activity and get information about pilot workload

#	author	title	Rel	expression	Def?	content/quotations/comments
77	Lee et al. [Lee07]	*Criterion To Estimate Optimum Lateral Static Stability Margin*	1	-	**NO**	-
78	Lee et al. [Lee05]	*Criteria To Select Directional Control Sensitivity*	2	-	**NO**	-
79	Lee et al. [Zai04]	*Criterion to Select Roll Control Sensitivity of Transport Aircraft with a Wheel*	1	-	**NO**	-
80	Lee, Rodchenko, Zaichik [Lee06]	*An Approach to Feel System Characteristics Selection*	1	-	**NO**	-
81	Lee et al. [Lee051]	*Effect of Pedal Feel System Characteristics on Aircraft HQ*	1	-	**NO**	-
82	Lee et al. [Lee071]	*Abrupt Response Criteria for Directional Control*	1	-	**NO**	-
83	Lemaignan [Lem05]	*Flying with no Flight Controls: Handling Qualities Analyses of the Baghdad Event*	1	-	**NO**	-
84	Love, Menich [Lov99]	*Method and apparatus for power control in a communication system using active demodulators*	2	Pilot Gain	**YES**	"Pilot Gain G_pilot" gain factor in control theory;
85	MacDonald, Hoffmann [Mac80]	*Review of Relationships Between Steering Wheel Reversal Rate and Driving Task Demand*	3	Control Activity, Workload	**NO**	"high values of SRR are indicative of high driving task demand"

#	author	title	Rel	expression	Def?	content/quotations/comments
86	McRuer [Gra03]	*A Flight Control Century: Triumphs of the Systems Approach*	4	High-Gain	**NO**	"Pilot action's can range from an essentially open-loop programmed controller to participation as a high gain, highly interactive controller element in a closed-loop pilot aircraft system." "These awkward at best and catastrophic at worst oscillatory situations can occur when the pilot is behaving as a very high gain controller within the closed-loop pilot-aircraft system." High Pilot Gain evokes instable behaviour;
87	McRuer [McR95]	*Pilot Induced Oscillations and Human Dynamic Behaviour*	5	High-Gain	**NO**	"Most of these high pilot gain tasks are well-defined flight operations. These nominal high gain tasks are normal and ordinary, whereas severe PIOs are extraordinary events." "TYPICAL TRACKING TASKS WITH HIGH PILOT GAIN/URGENCY: Aerial Refueling, Formation Flying, Precision Tracking, Precision Approaches and Spot Landings (e.g., carrier approach), Terrain Folling, Demanding/Unexpected Transitions" "high-gain, compensatory system, pilot behavior." "EXCESSIVE PILOT GAIN" as source of PIO; "the pilot is exerting full-attention, high-gain closed-loop control"; "to determine the pilot gain,Kpl," "[...]high PIO potential in urgent, high-gain tasks."; "It has been well-known for many years that the pilot gain required to accomplish precision high-gain";

#	author	title	Rel	expression	Def?	content/quotations/comments
87	McRuer [McR95]	*Pilot Induced Oscillations and Human Dynamic Behaviour*	5	High-Gain	**NO**	"type of pilot behavior (e.g., compensatory or synchronous), pilot gain levels, nominal high-gain pilot-vehicle system bandwidths, various sensitivities to effective vehicle characteristics, etc."
88	McRuer et al. [McR69]	*a systems analysis view of longitudinal flying qualities*	2	Pilot Gain	**YES**	"Kp Pilot gain" gain factor in control theory, bandwidth;
89	Mitchell, Hoh [Mit94]	*The Measurement and Prediction of Pilot-in-the-Loop Oscillations*	3	Pilot Gain (without using the expression)	**NO**	"PIO Tendency Classification Scale: Pilot Initiated Abrupt Maneuvers-> causes oscillations?" different types of PIOs and the contributors;
90	Mitchell, Klyde [Mit06]	*Identifying a PIO Signature - New Techniques Applied to an Old Problem*	4	High-Gain, Pilot Gain	**NO**	"In flight test, higher gain or urgency maneuvers that can expose PIO indicators are often not performed, because they lack operational relevance,"; "Figure 2. Pilot gain increases as the aircraft approaches the refueling drogue." "Closed-loop pilot-vehicle system: […]PIO shows itself in those closed-loop scenarios that can result in reduced pilot-vehicle system stability margins, such as the probe-and-drogue aerial refueling task [...]. The pilot typically responds with higher gain inputs in such scenarios due to the nature of the task, environmental conditions, or an unpredictable aircraft response, such as that associated with actuator rate limiting."; "It is very common for oscillatory behavior to appear in time responses, especially during periods of high-gain, closed-loop pilot activity."

#	author	title	Rel	expression	Def?	content/quotations/comments
91	Moreira, Paglione, Siqueira [Siq07]	*Robust Flight Control Design Supported by Flying Qualities Analysis*	1	-	**NO**	-
92	Mycynek [Myc03]	*Bandwidth stabilized PLL*	2	Pilot Gain	**NO**	"Pilot Gain Error Signal"
93	Neal, Smith [Nea70]	*An In-Flight Investigation to develop Control System Design Criteria for Fighter Airplanes*	3	Pilot Gain	**YES**	"K_BW Pilot gain at omega= (BW)min (lb/deg)" list of abbreviations; "K_p Steady-state pilot gain (lb/deg)" list of abbreviations; "The model of the pilot consists of a variable gain (K_p).";
						"The pilot comments indicate quite clearly that he wants to acquire the target quickly and predictably, with a minimum of overshoot and oscillation. The question that remains is how to translate this observation into nathematical terms." description tracking-"style"; "The comments concerning tracking forces are probably related to the pilot's gain"; "Thus 1 would appear that high control sensitivity somehow causes an increas in high-frequency pilot gain"; "A better understanding is needed of the effects of pilot gain, per se, on flying qualities.";
94	Nguyen et al. [Ngu05]	*Implementation of a Large Airplane Simulation Model to Support Pilot Model Development*	1	-	**NO**	-

#	author	title	Rel	expression	Def?	content/quotations/comments
95	Niewind [Nie11]	*What the Hell is Pilot Gain?*	5	Pilot Gain	**YES**	"The term "pilot gain" essentially describes the way the pilot acts on the inceptor during flight"; "Both dispositions have their advantages and disadvantages and none is generally superior to the other"; comparison of low and high gain pilots; famous synonyms; "Nearly all of them used the term "aggressiveness" to explain pilot gain" survey!
96	Niewind [Nie111]	*Investigations on boundary avoidance tracking and pilot inceptor workload*	5	Pilot Gain	**YES**	"Furthermore, defining pilot gain itself is a challenging task [16]."; "He, therefore, moves the stick controller with high pilot gain."; "Gray's pilot inceptor workload criterion, a new pilot gain measure"; "Pilots are asked to perform manoeuvres intentionally high or low gain, time-bounded assessments intend to increase the pilot gain by increasing the task urgence and handling qualities during tracking (HQDT) is a task specifically tailored to expose hidden PIO tendencies"; "extreme pilot gain during point tracking"."
97	Onstott, Faulkner [Ons77]	*Prediction, Evaluation, and Specification of Closed Loop and Multiaxis Flying Qualities*	3	Pilot Gain, Workload	**YES**	Definitions of Pilot Workload; "K=Pilot Model Gain"; gain factor in control theory

#	author	title	Rel	expression	Def?	content/quotations/comments
98	Pew [Pew05]	*Some History of Integrated Human Performance Models (PPT-Präsentation)*	1	-	**NO**	-
99	Pourtakdoust, Shajiee [Pou05]	*Development of an Optimal Software-Pilot Rating Scale for Flight in Turbulence Evaluation*	3	Pilot Gain	**YES**	"K_p is the pilot gain"; gain factor in control theory; "Consequently the pilot workload can be obtained as a function of some pilot parameters. In this study a pilot rating scale is taken which penalizes both excessive pilot effort as well as excessive aircraft response." Pilot effort as Pilot gain?;
100	Raney, Jackson, Buttrill [Ran02]	*Simulation Study of Impact of Aeroelastic Characteristics on Flying Qualities of a High Speed Civil Transport*	4	High-Gain, Workload	**YES**	"DEFINITIONS FROM TND-5153: [...] WORKLOAD: The integrated physical and mental effort required to perform a specified piloting task."; "Evaluate handling qualities in landing for a high-gain task."
101	Roscoe, Alan H. [Ros79]	*Handling Qualities, Workload and Heart Rate*	4	Workload	**YES**	several definitions of workload existing; "Another method of assessing HQ and levels of workload, especially during landing approaches, is by measuring control activity. Morrison and Stimely (9) quantified pitch activity and used the results to augment pilot's subjective impressions of workload during noise abatement approaches. Barber et. al. (10) summated force inputs from elevator, aileron and rudder to give a workload factor during the evaluation of general aviation aircraft HQ. Nevertheless these autors accepted that using force inputs to give a workload factor "... has some deficiences""

#	author	title	Rel	expression	Def?	content/quotations/comments
102	Roscoe, Alan H. [Ros78]	*Assessing Pilot Workload (AGARDograph No. 233)*	3	Workload	**YES**	literature about the assessment of pilot workload
103	Shweyk, Weltz [Shw05]	*Design and Validation of Flight Control Law Changes Intended to Minimize Pilot-Induced Oscillations in a Large Transport Aircraft*	4	High-Gain, Pilot Gain	**NO**	"In the early development of the C-17A Globemaster III, incidents of lateral PIO were encountered during the approach and landing phase of flight. Some of these encounters took place during normal high gain piloting tasks"; PIO/Pilot Gain!; "Command Gain" gain factor;
104	Sibilski, Lasek, Ladyzynska-Kozdras, Maryniak [Sib04]	*Aircraft Climbing Flight Dynamics With Simulated Ice Accretion*	1	-	**NO**	-
105	Smith, Berry [Smi75]	*Analysis of Longitudinal Pilot-Induced Oscillation Tendencies of YF-12 Aircraft*	4	Pilot Gain	**NO**	"The first, which is more common, takes place during aerial refueling when the pilot gain is high. The pilot tends to interact with the aircraft's SAS-on short-period and structural modes. […] the PI0 occurred during refueling, where pilot gain was high." "The task is demanding and requires tight, attentive attitude control on the part of the pilot [...] However, the attitude changes act as triggering cues under conditions of high pilot gain and result in a coupled interaction. Aerial refueling; "A small-amplitude PI0 tendency near a frequency of 1 cycle per second existed when the pilot gain was high during refueling" mix-up pilot gain/pilot model gain;

#	author	title	Rel	expression	Def?	content/quotations/comments
106	Smith, Edwards [Smi80]	*Design of a nonlinear adaptive filter for suppression of shuttle pilot-induced oscillation tendencies*	2	Pilot Gain	**YES**	"K_p,theta Pilot Gain" gain factor in control theory;
107	Spyker, Stuckhouse, Khalafalla, McLane [Spy71]	*Developments of Techniques for measuring pilot workload*	2	Workload	**NO**	-
108	Sung, Tong [Sun]	*A Projection-based Semi-Blind Channel Estimation for Long-Code WCDMA*	2	Pilot Gain	**YES**	"G the pilot gain." gain factor in control theory;
109	Theunissen et al. [The05]	*Terrain Following and Terrain Avoidance with Synthetic Vision*	4	Control Activity	**NO**	"To achieve accurate tracking performance combine with low control activity, a prediction based augmentation concept [1] is used to support the manual control task."
110	Tomayk [Tom00]	*Computers Take Flight – A History of NASA'S Pioneering Digital Fly-by-Wire Project*	3	Pilot Gain	**YES**	"The pilot used three four-position switches on the mode control panel to select a particular gain. Position three was optimal, as well as anyone could tell before a flight. Number four was a higher gain; numbers one and two selected a lower gain."; "different gain settings."; "The pilot also must be in a "high gain" situation, such as landing or tight tracking. Otherwise, the PIO is not likely to show up." "Gain—a predefined coefficient that is applied in the control laws of a fly-by-wire aircraft to affect the sensitivity of the results of a command."

#	author	title	Rel	expression	Def?	content/quotations/comments
110	Tomayk [Tom00]	*Computers Take Flight – A History of NASA'S Pioneering Digital Fly-by-Wire Project*	3	Pilot Gain	**YES**	"The values of the gains could be altered in software and a range of gains could be selected using rotary switches on the mode control panel."; "High gain model following—a method of monitoring performance by comparing actual values to optimal predicted values."
111	van der Geest, Hosman, Schuring [Hos051]	*Pilot Model Development for the Manual Balked Landing Maneuvre*	4	Aggressiveness, Pilot Gain	**YES**	"Varying the bandwidth of the pilot model - aircraft open loop by adjusting the model parameters simulates more aggressive or relaxed pilot behavior."; "When a pilot tries to improve tracking performance, he will increase his gain. [...]A too high gain will reduce the stability of the control loop."; "pilot gain Kh";
112	van der Vorst [Vor01]	*A Pilot Model for Helicopter Manoeuvres*	2	Pilot Gain	**YES**	"Ke equivalent pilot gain" gain factor in control theory;
113	van der Weerd [Wee00]	*Pilot-Induced Oscillation Suppression Methods and their Effects on Large Transport Aircraft Handling Qualities*	4	Pilot Gain	**NO**	definition PIO: "inadvertent, unwanted aircraft attitude and flight path motions that originate from anomalous interactions between the aircraft and pilot. PIO tendency is an indication of a handling qualties deficiency and usually only occurs when the pilot attempts tight closed-loop control of the aircraft"; Overcontrolling often occurs with inexperienced pilots or experienced pilot flying a new type for the first time; "as the pilot increases his gain in a task";

#	author	title	Rel	expression	Def?	content/quotations/comments
114	van Houten [Hou99]	*Attentional Effects of Superimposing Flight Instrument and Tunnel-in-the-Sky Symbology on the World*	2	Workload	**NO**	"Attention and workload were manipulated by adding a manual speed control task and/or a detection task";
115	Verwey [Ver90]	*Adaptable driver-car interfacing and mental workload: A review of the literature*	3	Workload	**NO**	Limitations in human information processing capacity, mental workload (car driver);
116	Warren [War06]	*An Investigation of the Effects of Boundary Avoidance on Pilot Tracking*	3	Pilot Gain	**NO**	"This theory presented that PIOs may result from increasing pilot gain resulting not from maintaining a specified condition, but avoiding imposed limits or boundaries on a specified task" (Gray);
117	Warren, Abell, Heritsch, Kolsti, Miller [War061]	*A Limited Investigation of Boundary Avoidance Tracking (Project HAVE BAT)*	5	Pilot Gain	**NO**	increasing pilot gain resulting from not maintaining a specified condition;
118	Weber, Efremov [Web05]	*Development of criteria for Flying Qualities Prediction using structural modelling of human pilot behaviour in the longitudinal precise tracking task*	2	-	**NO**	Tracking Task; Human Pilot Behaviour
119	Weltz, Shweyk, Murray [Wel07]	*Application of New and Standard Pilot-Induced Oscillation (PIO) Analysis Methods to Flight Test Data of the C-17 Transport Aircraft*	4	Pilot Gain	**NO**	"Some of these incidents took place during normal high gain piloting tasks"; "there is unnecessarily high gain"; "changing pilot gain" gain factor in control theory; "The highly demanding combat environment and the resulting high pilot workload"; "Pilot Model Gain" !; "high gain pilot" individual;

#	author	title	Rel	expression	Def?	content/quotations/comments
120	Willemsen, Duda, Heintsch, Luckner [Wil99]	*PIO-Kriterien für Verkehrsflugzeuge*	2	Workload	**NO**	"Es wurde eine anspruchsvolle Flugaufgabe ausgewählt, um eine hohe Arbeitsbelastung des Piloten zu erreichen, was erfahrungsgemäß auch hohe Pilotenverstärkungen zur Folge hat und deshalb für PIO-Untersuchungen geeignet ist." Are PIO-criteria transferable to airliners?
121	Witte [Wit04]	*An Investigation Relating Longitudinal Pilot-Induced Oscillation Tendency Rating to Describing Function Predictions for Rate-Limited Actuators*	4	High-Gain, Pilot Gain	**YES**	"This criterion consists of the product of additional pilot gain and the normalized maximum amplitude of the commanded actuator necessary to cause PIO."; "Kp = Neal-Smith Pilot Gain" gain factor in control theory; "low gain/high gain task"; "This is possibly due to the high gain, high bandwidth piloting technique used in this task while the other tasks were more focused on task performances which required both high and low gains and bandwidths"; bandwidth;
122	Yaroshevsky et al. [Yar05]	*A Validation Plan for Pilot Models Developed for New Larger Airplanes*	1	-	**NO**	-

Table 2-1: Table of Bibliographical References

3 Psychological and Physiological Aspects of Pilot Gain

The literature review in chapter 2 showed that pilot gain is a phenomenon which cannot easily be captured – every pilot holds a whole bandwidth of control behaviour and moreover each pilot offers another bandwidth.

As different pilots show different control behaviour and perform differently on the same task, the question arises: Why is there such individual pilot gain?

[Nie11] proposes the hypothesis of individual disposition and physiology correlating with individual pilot gain.

3.1 Objectives

There are no examples in literature describing a proven connection between pilot gain and the individual yet. Therefore the approach is expanded to an interdisciplinary research on relations between human closed-loop control behaviour and individual disposition and physiology. Still, then it must be borne in mind whether results are transferable to pilot gain.

What is looked for is ideally meeting the following requirements:

1. *Manual human closed-loop control behaviour in tasks where the recorded results are not (only) about accuracy of a task but about speed, aggressiveness and frequency,*
2. *in connection with personalised measures*
   (not only fundamental human limits)
   preferably without temporary influences like fatigue or anxiety.

3.2 Approach

Various sciences are addressed by this question, which form intersections again including established disciplines: Constructs describing the answers are suspected somewhere in between psychology, biology, engineering science and sport science.

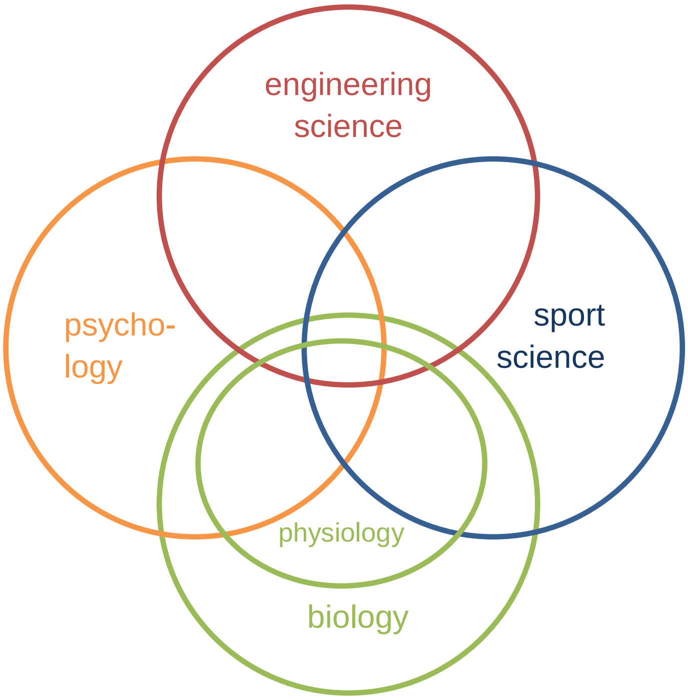


Figure 3-1: Interdisciplinary research on individual closed-loop control behaviour

Figure 3-2 helps to get a general idea of what fields the conducted research was done in:

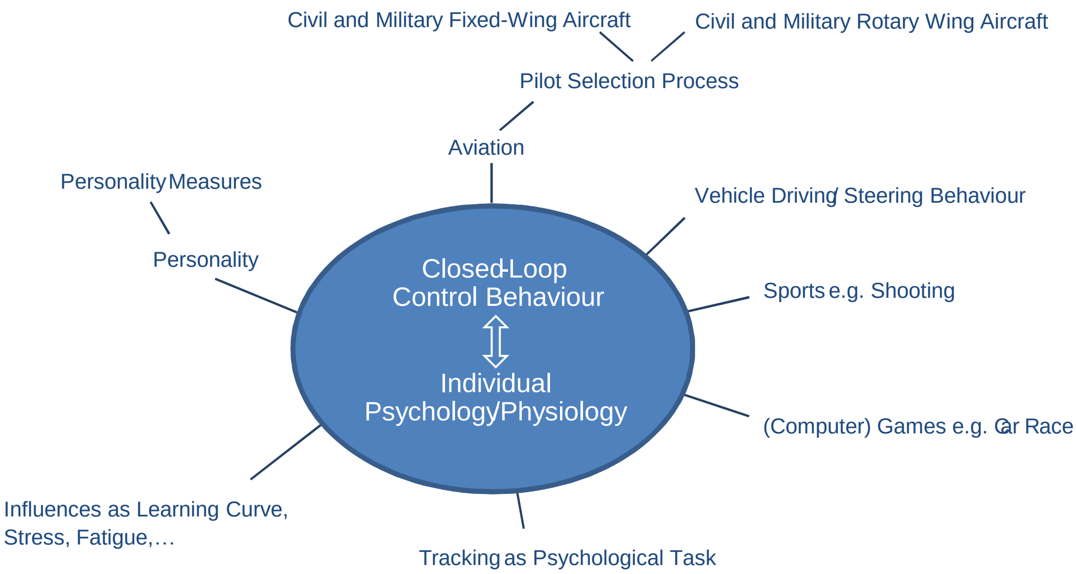


Figure 3-2: Review of ideas investigated on

As pilot gain is a phenomenon of aviation, an increased interest is set on investigations done in this field: When it comes to human control behaviour, are there any known relations, for example in the pilot selection process or pilot training?

Other fields, in which scientific studies on human closed-loop control behaviour are suspected, are vehicle driving, sports or computer games involving inputs on for example a joystick or mouse. Tracking is also utilized as psychological task and therefore also possible offers answers.

Knowledge about definitions of personality and personality measures is necessary to make individuality more tangible.

Moreover there are possibly many other factors influencing the individual control behaviour like anxiety, stress, learning effects, fatigue and more which are looked for without mainly focussing on.

3.3 Results of Research

This chapter will at first give an idea of how personality is made tangible and measurable. Moreover results of the research done will be presented as well as a discussion of how a test investigating on correlations between individual pilot gain and psychological aspects could be set up.

3.3.1 Human Personality

Theories about structures in personality trace back to centuries of trying to capture personality. Each human being is an individual who is more complex than any machine ever could be.

His behavior is affected by a multitude of influences which makes it impossible to ever be completely determined or predictable. Still, personality is reflected in behaviours that are relatively stable over time.

3.3.1.1 Measuring Personality

Several attempts have been made to measure personality. A categorization which still plays a large role in personality psychology was presented by Eysenck in the 60s of last century. Two major personality factors, were presented [Eys1] :

- Neuroticism
- Extraversion

Figure 3-3 shows typical adjectives describing high and low neuroticism and extraversion: Neuroticism is indicated as vertical, extraversion as horizontal. The more extraverted a person, the higher is his value for extraversion. The less emotionally stable a person, the higher is his value for neuroticism.

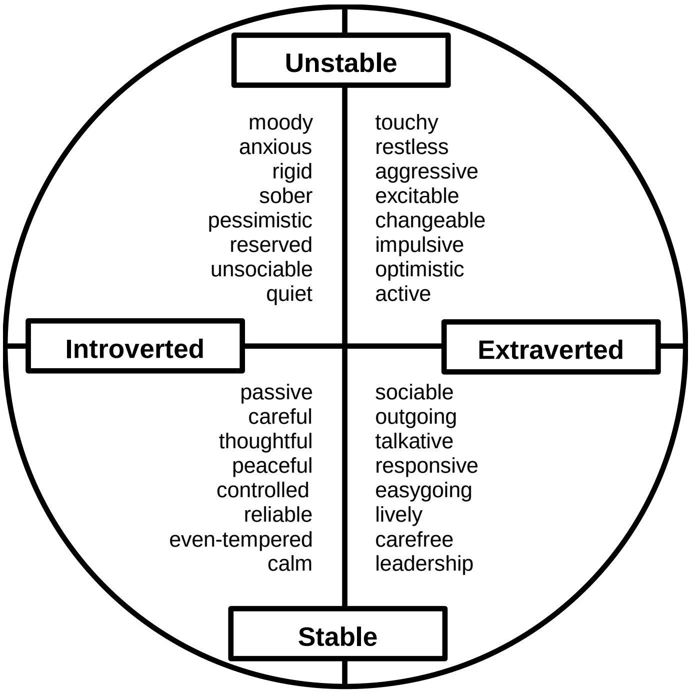


Figure 3-3: Characteristics for the personality traits extraversion and neuroticism [Eys]

It is hypothesised that extraversion and neuroticism could be the personality types that are most likely to distinguish people into high gain and low gain pilots [Nie11]. As a consequence, the research concentrated on these two traits.

These personality traits can also be found in the Big Five-model of personality [McC87] which besides neuroticism and extraversion also includes:

- Openness to experience
- Conscientiousness
- Agreeableness

As a matter of fact this classification of personality is still utilized in many psychological studies, especially in the USA.

3.3.1.2 Personality Questionnaires

To make personality measurable, personality questionnaires were developed. The content and therefore the included questions depend on the purpose of the questionnaire which led to a multiplicity of existing personality questionnaires over the last decades. Personality questionnaires are self-report instruments which may lead to the questionnaire painting a picture of a person which may not completely reflect reality.

One of the first personality questionnaires was the Eysenck Personality Questionnaire (EPQ), later EPQ-R, which is based on Eysenck's theory of personality. It contains amongst others 24 items to assess neuroticism and 23 items to assess extraversion. To each item a "yes" or "no" answer is asked for.

The neuroticism scale measures the degree to which the individual is predisposed to experience negative effect. People with high neuroticism tend to be moody and worried and to experience loneliness, guilt and sadness.

Examples of the neuroticism scale are questions like: "are you a worrier?", "would you call yourself tense or highly-strung?" and "do you often feel lonely?"

The extraversion subscale assesses the degree to which a person is sociable, active and impulsive. Individuals with high extraversion tend to be talkative, outgoing and they often tend to seek for excitement.

Examples of the extraversion scale are questions like: "are you a talkative person?", "are you rather lively?" and "do you enjoy meeting new people?" [Wei10] .

3.3.2 Personality/Physiology and Individual Closed-Loop Control Behaviour

3.3.2.1 Games

As fast human closed-loop control behaviour is needed to succeed in many computer games (for example car races) and often inputs are applied by joystick or something similar. Thus, some research in this area concerning individual control behaviour was suspected.

The only study found being closer to the question is related to control behaviour on a computer and concerns computer mouse movement [Trä91] : 64 subjects had to conduct 1200 cursor positioning trials over a period of two days.

Results were that the subjects were strongly accuracy-oriented which resulted in a small number of errors (the opposite would be speed-orientation). Horizontal cursor movements take about 10% more time than vertical cursor movements. The results also show that the c:d-ratio, which is the mouse movement distance necessary per distance unit of the cursor movement (on the display) did not influence the positioning time. Short positioning times are furthered by low necessary accuracy. A learning effect was investigated.

Horizontal cursor movements taking more time than vertical cursor movements probably points out to a general human limit which should be kept in mind when comparing pitch and roll tracking tasks. Possibly the lacking ability of moving the arms and hands any faster could make a pilot change his tracking strategy.

Another test which was performed to find correlations between personality and gaming behaviour concerns the game "Guitar Hero" [Fer07] . The game includes body movements like pretending to play the guitar. As personality trait, extraversion was examined. The result was that the relation between extroversion / introversion and body movements is not clear. It is assumed that extroversion is consistent with more gesticulation and a greater variety of facial expressions. Activity level is a facet of extroversion and hence it can be reasonable to assume that extroverts show more body movements in everyday life as well as in specific contexts like gaming.

This would be in line with extraverted pilots rather being high gainers.

3.3.2.2 Sports

In relation to pilot gain, some pilots could be faster than others not just because of reaction time but also because of motoric abilities or training which leads to a research in the field of sport sciences.

Human closed-loop control behaviour is a well-known expression among sport scientists. Nearly every movement of the human body is categorized “closed-loop”.

One fact influencing the individual’s speed of performing a movement is the composition of human muscles. Although training on speed can be performed, some people are “born” sprinters while others are not.

Human muscles contain 2 groups of muscle fibres: fast twitch and slow twitch. The percentage of fast and slow twitch in every individual is genetically determined. Whilst fast twitch-fibres are mainly used for fast and intense tasks, slow twitch-fibres are mainly used for tasks less intense [Wei101] . Depending on the sport an individual is doing, training of one or the other type of muscle fibre is supported.

Other literature found about sport including individuality, even personality aspects, concentrates on sport success, team sports or others.

3.3.2.3 Vehicle Driving

Although there is a huge amount of literature about human in road traffic, no studies describing how steering behaviour and personality correlate were found.

Closest to the question is a study about human vehicle control which describes different steering strategies including classifications for example the amount of error-correction including driver models [God84] .

Other literature concentrates on driver personality correlating with Speeding, Agressiveness of Driving, Risk-Taking or Alcohol, exemplarily [Shi78] .

3.3.2.4 Aviation

It is noticeable that in the field of aviation there is an immense interest in properly modelling the pilot's control behaviour mathematically and therefore human capacity of information processing and motor response is modelled. Various components of the human body are considered.

Concerning the pilot selection process, the human capacity of information processing and motor response is investigated on to a certain amount as basic cognitive and psychomotor skills. Personality screening is only done to a certain amount at which the most important reason is the critical reliability [Goe04] .

During the research, the pilot selection process of Deutsches Zentrum für Luft- und Raumfahrt (DLR), Flugmedizinisches Institut der Luftwaffe (FlMedInstLw) and Luftfahrerschule für den Polizeidienst (LFSfPD) was investigated. The investigation included, next to the selection process itself, interviews with psychologists, psychiatrist, pilots and pilot instructors.

Still, no effort to study correlations between personality / individual physiology and the individual closed-loop control behaviour was found.

3.3.2.5 General Psychological Tests and Studies

Next to research on correlations within the different disciplines, psychological studies verified by a test process were examined. A small selection is presented in this subchapter.

Most of the time, the test procedure is rather simple and not very specific to a certain purpose. Still, some result could possibly support the theory of individual pilot gain being caused by different personality structures. However before drawing conclusions to pilot gain, it is important to carefully examine the respective study and the conditions under which it was performed.

One of the studies is a test examining the difference between reaction time (RT) and movement time (MT) among extraverts and introverts:

The traditional measure of response time includes the time from stimulus onset to the press of a target button. However, RT can be measured independently of MT by an apparatus making use of a "home"- button. RT is recorded as the time from stimulus onset to the release of the home button, while MT is recorded as the time from this release to the subsequent press of a target button [Dou97] .

RT is an index of cognitive processes and includes time relating to stimulus classification or evaluation, response selection, and programming the execution of motor movements. No difference between extraverts and introverts was found for RT.

The overall MT is only minimally affected by task difficulty and as such is appropriately used as measure of the speed of movement within responses.

The result included that extraverts showed faster movements than introverts. It is the early phase of MT that is associated with differences in extraversion. It is likely that introverts and extraverts have equal average velocities, or equal peak velocities, but extraverts accelerate to that velocity faster than introverts [Dou97] .

Transferred to the theory of high gain pilots being rather extraverted this result would be in line with their high gain control behaviour.

It is hypothesized that the response strategy behind is what differs introverts from extraverts: introverts tend to self-select strategies that match position (accuracy strategy) while extraverts tend to favour strategies that match velocity (speed strategy) [Fri71] .

Moreover in a psychomotor test measuring speed, impulsiveness was found to correlate significantly with extraversion [Gud80] .

In another personality study differentiating between the dimensions extraversion and neuroticism, handwriting was investigated. The largest writers and those who wrote the least in any given space were the low neurotic extraverts, while the smallest writers were high neurotic extraverts. The fastest writers were the high neurotic extraverts [Taf67] .

All in all it seems as if extraverts in general tend to apply higher speed than introverts in different situations.

3.3.3 Personality/Physiology and Individual Pilot Gain

Decades after the publishing of Eysenck’s personality theory and the attempt to explain how personality traits can be explained by psychophysiological phenomena, there is no clear evidence [Lan051] . Concerning this correlation, there is no clear position but contradictory test results in psychological literature.

The only way to find out whether pilot gain and personality or motoric behaviour correlate, is by performing a test, which is able to reflect the pilot’s natural gain as good as possible, in combination with a personality questionnaire adapted to the purpose [Nie11] .

3.4 Conclusion

No practical example of personality or individual physiology influencing closed loop control behaviour was found. There are different approaches to explain how processes in a human brain could influence motoric behavior but in accordance with the current state of science, a possible correlation could only be figured out by an empirical study.

Interestingly, already in 1971, in a study of driver control movements the assumption is made that frequency and signal from the controller form an index of the effort of the operator in tracking, and frequency differences between individuals may reflect differences in tracking [McL71] .

Possible explanations, why no psychological studies followed, are that it is an interdisciplinary question no discipline feels completely responsible for, that there is no obvious need for the results (for example compared to collecting personality information to predict the likelihood of a pilot completing his studies) and it is a complex question.

Although human control behavior has been investigated on for decades, most of the time the focus is on general human limitations, not on the individual.

4 Measures of Pilot Gain

It is unlikely that there will ever be a pilot gain measure which provides a universally valid range of values that are associated with low, medium or high gain flying in all situations. A pilot gain parameter will always have to be considered in context with the task, the aircraft dynamics and the inceptor. What one can hope for is a pilot gain measure that allows the evaluation of different gains in comparable situations [Nie11] .

Multiple approaches were made to measure pilot gain. In an on-going test campaign, several measures were introduced and are reviewed for their suitability, some seeming to be more suitable than others. While measures of deflection, speed and acceleration or alternatively measures of power spectral density in frequency domain seem to represent pilot gain rather well, tracking accuracy or pilot model components do not [Nie11] .

25 measures (Table 4-3) were chosen in [Nie11] as parameters (introduced and explained in blue writing within the following chapters) and are compared in this thesis in order to find out whether relationships between them can be identified. For example: if parameter A increases, does parameter B increase as well?

The main question is: Which of these parameters correlate with each other?

Figure 4-1 illustrates the principal approach: For 23 performed simulator runs, respectively one value for every parameter (representing a possible pilot gain measure) was obtained. Via correlation analysis in MATLAB, the connection between each possible pair of parameters can be assessed and illustrated in a correlation matrix. Moreover a plot for every possible correlation is created.

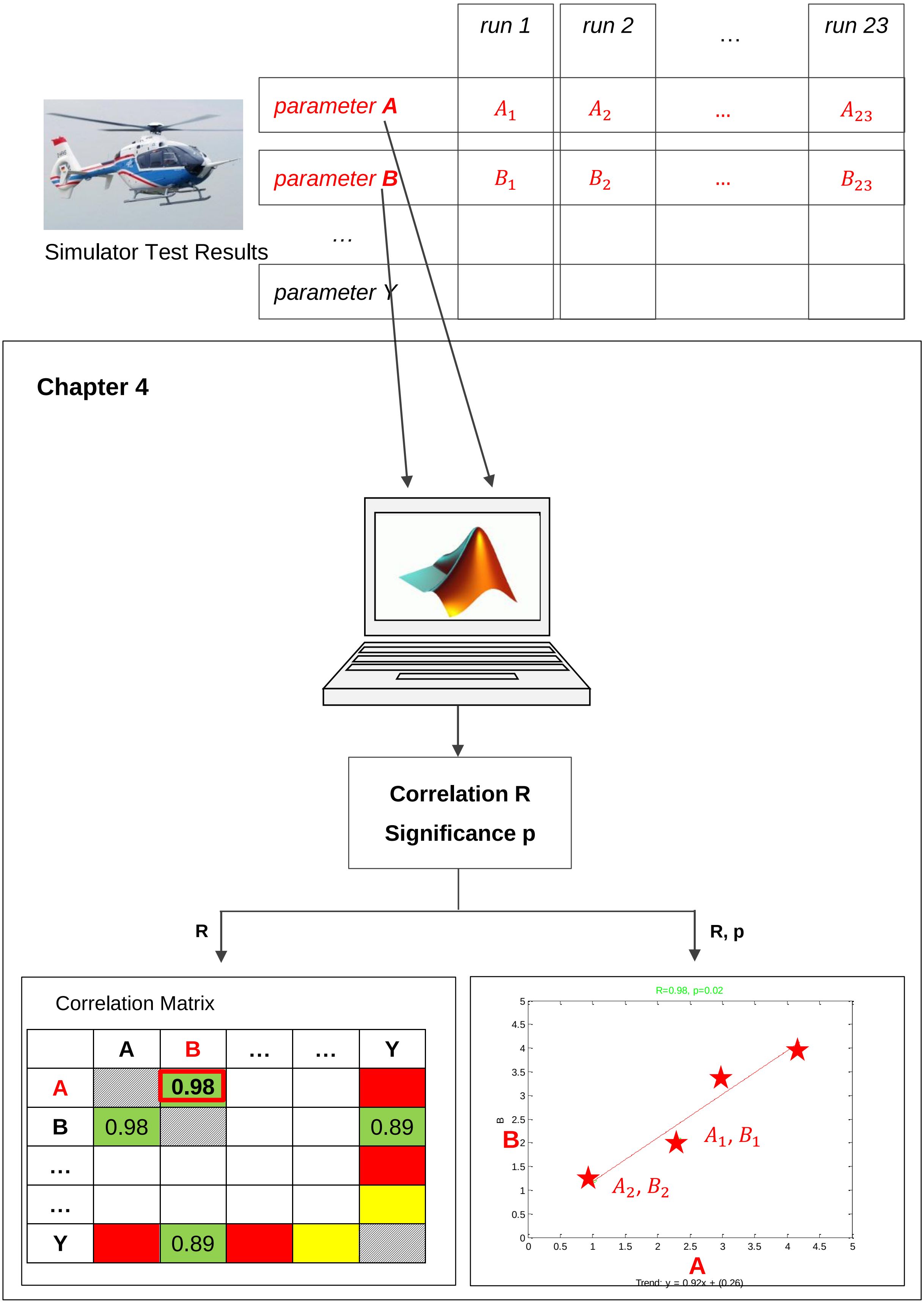


Figure 4-1: Principle approach in correlation analysis [cha12]

The following subchapter provides some basic mathematics and statistics to ensure a better understanding of the further procedure. Afterwards an overview is given of how measured data was obtained by test and simulation. The 25 measures and the relations between them are explained and discussed in the correlation analysis afterwards.

4.1 Mathematical Background

4.1.1 (Arithmetic) Mean

The arithmetic mean is defined as [Bro76] :

$$\bar{x} = \frac{1}{n}\sum_{i=1}^{n} x_i = \frac{1}{n}(x_1 + x_2 + \cdots + x_n) \qquad \textbf{(4-1)}$$

at which n is the number of values $x_1, x_2, \dots, x_n$.

If only absolute values are considered, the arithmetic mean can be expressed by means of the L_1 – norm $||x||_1$ [Alt99] :

$$\bar{x}_{L_1} = \frac{1}{n}\sum_{i=1}^{n} |x_i| = \frac{1}{n}||x||_1 \qquad \textbf{(4-2)}$$

4.1.2 Root Mean Square

The root mean square, also known as quadratic mean, is defined as [Bro76] :

$$RMS = \sqrt{\frac{1}{n}\sum_{i=1}^{n} x_i^2} = \sqrt{\frac{1}{n}\left(x_1^2 + x_2^2 + \cdots + x_n^2\right)} \qquad \textbf{(4-3)}$$

at which n is the number of values $x_1, x_2, \dots, x_n$.

The root mean square, expressed by means of the L_2 – norm$||x||_2$ [Alt99] :

$$RMS_{L_2} = \sqrt{\frac{1}{n}\sum_{i=1}^{n} x_i^2} = \sqrt{\frac{1}{n}}||x||_2 \qquad \textbf{(4-4)}$$

Compared to the (arithmetic) mean, large deviations from a mean value are taken into account to a greater extent.

4.1.3 Correlation

In statistics, correlation R is a non-dimensional measure of how certain parameters are connected with each other without necessarily stating a cause-and-effect relationship or direct dependence.

Correlation can be calculated according to equation (4-5) [Bac11] :

$$R_{x_1,x_2} = \frac{\sum_{k=1}^{K} (x_{k1} - \bar{x}_1)(x_{k2} - \bar{x}_2)}{\sqrt{\sum_{k=1}^{K}(x_{k1} - \bar{x}_1)^2 \sum_{k=1}^{K}(x_{k2} - \bar{x}_2)^2}} \quad \textbf{(4-5)}$$

$x_{k1} = parameter\ value\ 1\ for\ object\ k$

$x_{k2} = parameter\ value\ 2\ for\ object\ k$

$\bar{x}_1 = mean\ of\ parameter\ value\ 1\ across\ all\ objects\ k$

$\bar{x}_2 = mean\ of\ parameter\ value\ 2\ across\ all\ objects\ k$

A correlation R can take values between -1 and 1, representing a perfectly positive/negative linear correlation for $R = 1/R = -1$. A correlation $R = 0$ indicates that the examined parameters do not correlate.

The bigger $|R|$, the smaller are the deviations from the linear trend.

Correlation does not say anything about a gradient or necessarily the actual function. Although being described by the same value R, the measured data behind can be completely different.

From an mathematical point of view, limitations are reached for $x_{k1} = \bar{x}_1$ or $x_{k2} = \bar{x}_2$, which represent a perfectly horizontal or vertical - in this case $R = 0$. This also includes periodic patterns like sine or cosine.

Illustrative example:

In ten runs, values for two different parameters x_{k1} and x_{k2} were measured (Table 4-1). After determining the arithmetic mean ($\bar{x}_1$= 5.50, $\bar{x}_2$ = 1.89), the value for correlation can be developed in few steps (4-6).

Run	Parameter x_{k1}	Parameter x_{k2}	x_{k1} - $\bar{x}_1$	x_{k2} - $\bar{x}_2$
1	4	1.2	-1.5	-0.69
2	2	1.0	-3.5	-0.89
3	8	2.9	2.5	1.01
4	9	3.0	3.5	1.11
5	6	2.0	0.5	0.11
6	7	2.4	1.5	0.51
7	1	0.8	-4.5	-1.09
8	3	0.9	-2.5	-0.99
9	5	1.5	-0.5	-0.39
10	10	3.2	4.5	1.31

Table 4-1: Measure data for calculating correlation as illustrative example

$$R_{x_1,x_2} = \frac{\sum_{k=1}^{K} (x_{k1} - \bar{x}_1)(x_{k2} - \bar{x}_2)}{\sqrt{\sum_{k=1}^{K}(x_{k1} - \bar{x}_1)^2 \sum_{k=1}^{K}(x_{k2} - \bar{x}_2)^2}} = 0{,}98 \qquad \textbf{(4-6)}$$

Figure 4-2 indicates parameter x_{k1} vs. x_{k2} as shown by Table 4-1, as well as a linear trend calculated by MATLAB.

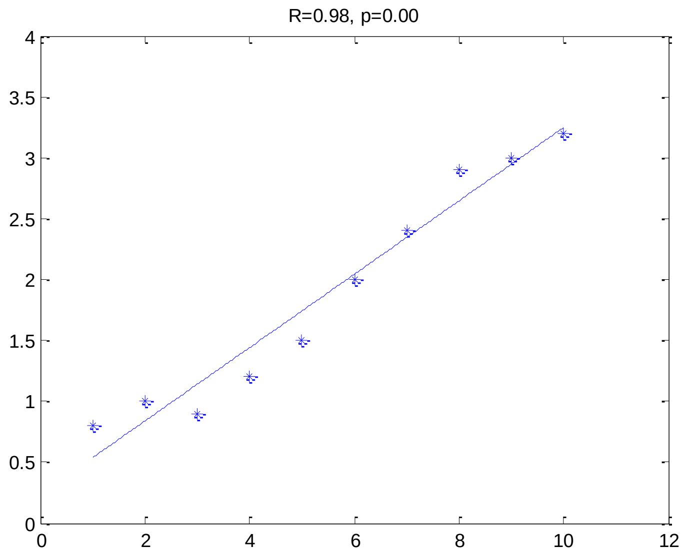


Figure 4-2: Illustrative example for correlation

4.1.4 Significance

Every time a correlation is calculated, another value comes with it to inform about the quality of the calculated correlation. This value is called significance.

Significance p as a measure expresses the probability that a correlation has come about by coincidence in terms of statistics. It can take values between 0 and 1, whereupon $p = 0.00$ represents a probability of 100%, saying that the probability that a correlation has come about by coincidence is equal to zero [Bac11] .

Both relevance and significance can be calculated by MATLAB via `corrcoef`. The elements located on the secondary diagonal of the matrices R (for relevance) and p (for significance) represent those values for a correlation x_1 vs. x_2 (see example; $R = 0.6546$, $p = 0.0007$).

Example:

```
[R,p]=corrcoef(X1, X2)

 R =

    1.0000    0.6546
    0.6546    1.0000
```

```
p =

    1.0000    0.0007
    0.0007    1.0000
```

4.2 Test

The German Aerospace Centre (DLR) tests adaptive open- and closed- loop systems on a Flying Helicopter Simulator (FHS). The FHS is controlled by fly-by-wire / fly-by-light and moreover has two active sidesticks.

In [Non10] Nonnenmacher aimed to develop a suitable technique to optimize an active sidestick's mechanical properties controlling a helicopter in the context of a diploma thesis. Data which was recorded in the context of this thesis was provided the author.

4.2.1 Test Setup

Both an experiment and a test environment were developed for the FHS ground simulation. Two displays and a module in MATLAB-SIMULINK were programmed which is able to vary sidestick parameters at the push of a button and providing the roll tracking task.

During the experiment, the sidestick's damping and eigenfrequency were diversified in rate (RC) and attitude command (AC) and evaluated both quantitatively and qualitatively [Non10]

Figure 4-3: Ground simulation of the Flying Helicopter Simulator [Non10]

4.2.2 Roll Tracking Task

The task which had to be performed by the test pilot was a roll tracking task as manual compensation regulation task. The task was at all times to minimise the bank angle error.

The bank angle error is defined as the difference between target and actual value of the bank angle:

$$\Phi_{Error} = \Phi_{target} - \Phi_{actual} \tag{4-7}$$

The bank angle error was indicated to the pilot by an artificial horizon via roll markers (green) (see Figure 4-4).

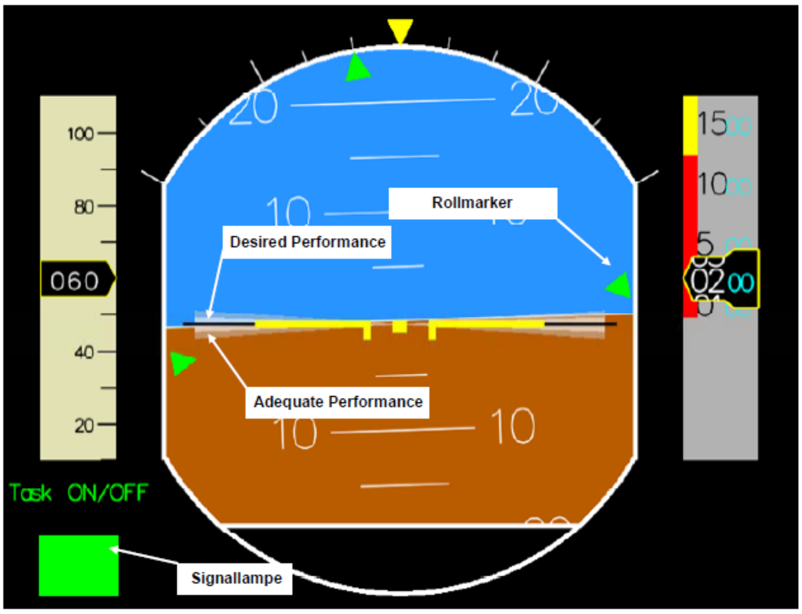


Figure 4-4: The bank angle error indicated to the pilot by an artificial horizon via roll markers [Non10]

For each run the same roll tracking task had to be performed. The signal sequence was described by the forcing function.

A forcing function can be generated in different ways: There are continuous signal sequences which were created as a sum of miscellaneous sine waves ("sum of sine" = SOS) and discrete signal sequences as for example square waves [Non10] .

According to the result of a GARTEUR research programme [Hov00] several test pilots were not able to choose a Cooper-Harper Rating for SOS roll tracking tasks. As the SOS-sequence is constantly changing, the test pilots are never able to minimise the angle error to zero. That is why it was impossible for some to assign a rating and the reason Nonnenmacher chose a discrete signal sequence for this task [Non10] .

After an optimization the discrete roll tracking task looked as shown by Figure 4-5:

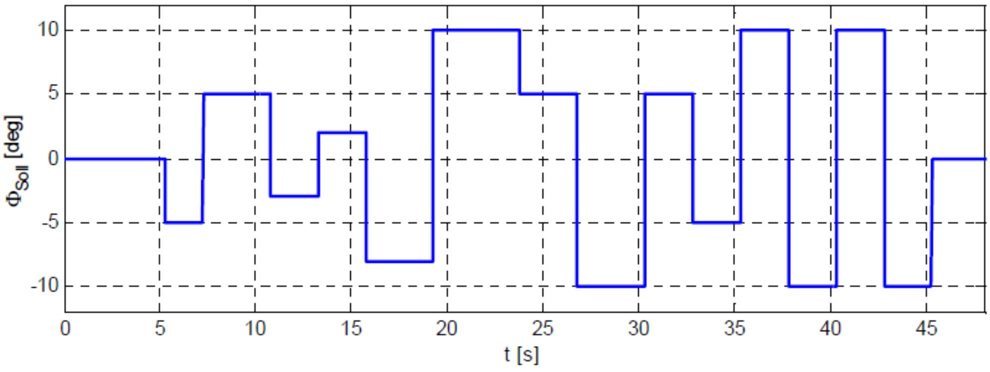


Figure 4-5: The roll tracking task as discrete signal sequence [Non10]

4.2.3 Test Execution

23 runs were performed with varying sidestick parameters as well as two different response types (attitude and rate command) (Table 4-2). Each run took 40 seconds.

The test pilot was an experienced DLR-helicopter pilot (4600 flying hours) who was allowed to familiarize himself with the task and helicopter dynamics before the actual test.

The actual test included one or two test runs for each sidestick parameter variation before the evaluation was done (Table 4-2 indicates the purpose of each run in column 3: T = test, E = evaluation).

Each evaluation was followed by the pilot filling in a questionnaire assessing the sidestick settings and stating a Cooper-Harper Rating (*CHRating*). The Cooper-Harper Rating (Figure 4-6) offers pilots an opportunity to evaluate handling qualities of an aircraft on a scale from 1 to 10, 1 describing excellent aircraft characteristics.

Run	Command	Purpose	ω_s [Hz]	k [N/deg]	D [-]
4	RC	T	3.0	2.0	1.1
5	RC	T	3.0	2.0	1.1
6	RC	E	3.0	2.0	1.1
7	RC	T	3.0	2.0	0.2
8	RC	E	3.0	2.0	0.2
9	RC	T	3.0	2.0	1.5
10	RC	E	3.0	2.0	1.5
11	RC	T	1.0	2.0	1.1
12	RC	E	1.0	2.0	1.1
13	RC	T	4.0	2.0	1.1
14	RC	E	4.0	2.0	1.1
15	AC	T	3.0	2.0	1.1
16	AC	E	3.0	2.0	1.1
17	AC	T	3.0	2.0	0.2
18	AC	E	3.0	2.0	0.2
19	AC	T	3.0	2.0	1.5
20	AC	E	3.0	2.0	1.5
21	AC	T	1.0	2.0	1.1
22	AC	E	1.0	2.0	1.1
23	AC	T	4.0	2.0	1.1
24	AC	E	4.0	2.0	1.1
25	RC*	T	3.0	2.0	1.1
26	RC*	E	3.0	2.0	1.1

Table 4-2: Stick settings, purpose and command mode for each run (*including breakout force) [Non10]

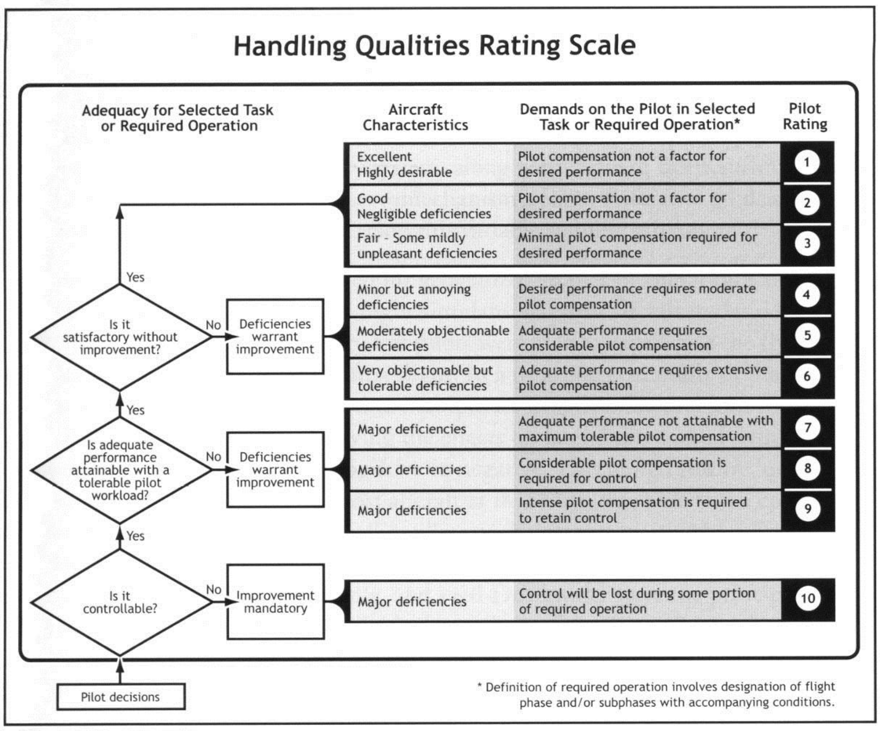


Figure 4-6: The Cooper-Harper Handling Qualities Rating Scale [Har84]

During each run, simulator data for the following variables was recorded every 8ms (sample rate = 125Hz).

- *StickCmd* [%]: deflection of side stick, normalized to a range between -1 and 1 (full deflection in both directions)
- *Stick Force* [N]
- *Angle* [rad]: actual pilot-controlled bank angle Φ_{actual}
- *Angle Task* [rad]: target bank angle Φ_{target}

4.3 Modeling and Simulation

The pilot's tracking behaviour can also be simulated by a pilot model. To gain values for the model parameters, parameter identification is performed. For this purpose the German Centre of Aerospace (DLR) provides FITLAB.

The MATLAB toolbox FITLAB comes with a graphical user interface which provides easy access to the standard tasks of reading the measured data, specifying the model and parameters, running the identification and looking at plots of the results [Seh06] .

The model structure is assumed to be known correctly and model parameters adjusted (parameter identification) so that the simulated model output matches the measured output for the same input history.

Two simple pilot models were chosen and identified [Nie11]

Pilot Model 1 (Point Tracking pilot model 1, PT1) [Nea70] is defined by the following transfer function:

$$F_1(s) = K_1 e^{-T_{e1} s} \frac{T_D s + 1}{T_I s + 1} \tag{4-8}$$

$K_1 = pilot\ model\ gain$ (*PT1_K*)

$T_{e1} = central\ processing\ delay$ (*PT1_Te*)

$T_D = lead\ time\ constant$ (*PT1_TD*)

$T_I = lag\ time\ constant$ (*PT1_TI*)

Moreover the parameter *PT1_QIE* was established, QIE shortening Quadratic Integral Error, as measure of how well the simulation matches the pilot's inputs (also see Figure 4-7).

$$QIE = \int_{t_{start}}^{t_{end}} (u_{pilot} - u_{model})^2 \, dt \tag{4-9}$$

PT1_QIE can be obtained by dividing QIE by the total amount of time $t_{end} - t_{start}$.

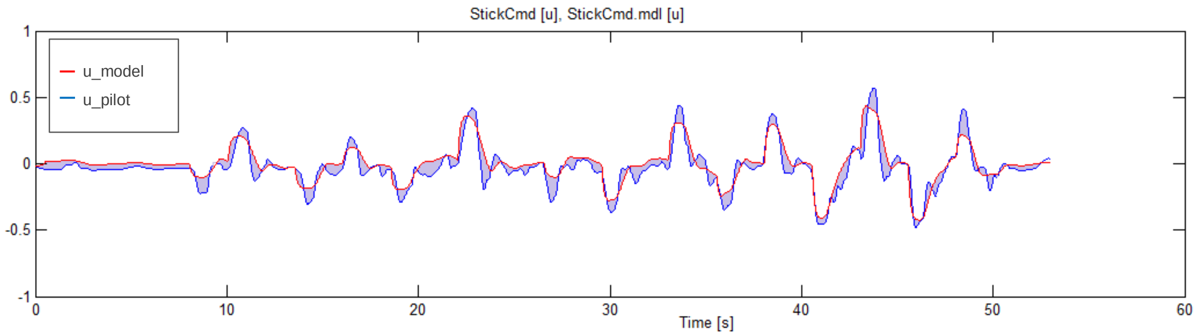


Figure 4-7: QIE as measure of how well the simulation matches the pilot's input

Pilot Model 2 (Point Tracking pilot model 2, PT2) [Dud95] is defined by the following transfer function:

$$F_2(s) = K_2 e^{-T_{e2} s} \tag{4-10}$$

$K_2 = pilot\ model\ gain$ (*PT2_K*)

$T_{e2} = central\ processing\ delay$ (*PT2_Te*)

Parameter *PT2_QIE* was calculated for each run corresponding to *PT1_QIE.*

4.4 Typical Measures of Pilot Gain

As pilot gain is characterized by the way the pilot acts on the inceptor, it seems reasonable to utilize the following measures as measures of pilot gain: stick deflection, stick speed, stick acceleration and error between desired and actual tracking.

4.4.1 Deflection

As already mentioned in chapter 4.2.3, the sequence of pilot's stick inputs for every run was recorded as *StickCmd.* For each run and each of the four following parameters one value was obtained from the whole sequence:

DeflectionMax: largest occurring absolute deflection per run

DeflectionMean: arithmetic mean (see chapter 5.1.1 (Arithmetic) Mean) of all absolute values of deflections

DeflectionRMS: root mean square (see chapter 5.1.2 Root Mean Square) of all deflections

DeflectionRMRatio: quotient of root mean square and mean

Figure 4-8 shows as an example the pilot's inputs on the sidestick during run004, Figure 4-9 shows the calculated above mentioned first three parameters.

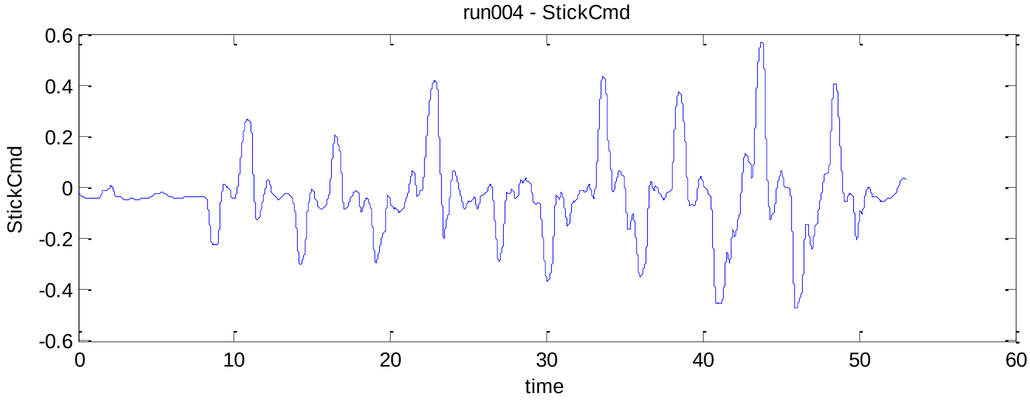


Figure 4-8: StickCmd (stick deflection) as recorded during run004

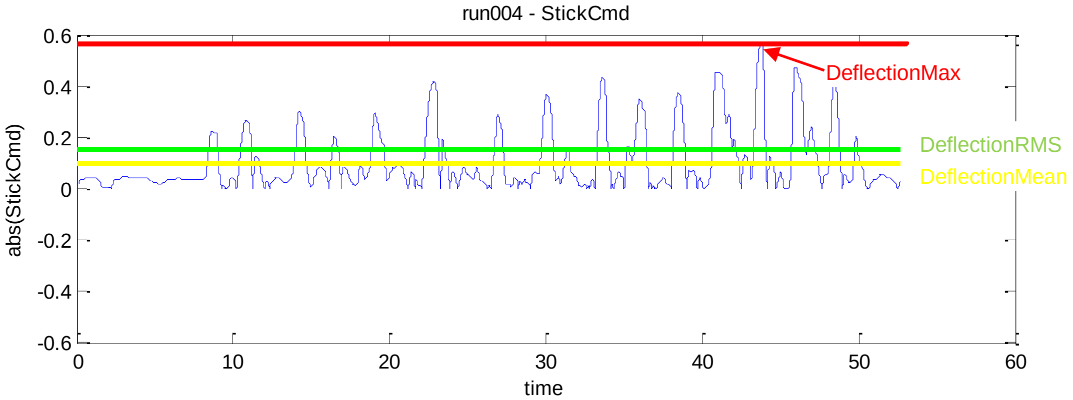


Figure 4-9: DeflectionMax, DeflectionMean and DeflectionRMS as calculated for run004

4.4.2 Stick speed

Four parameters describe the stick speed (deflection rate), calculated from *StickCmd* for each run. The stick speed over time is calculated according to (4-11) as a basis to obtain the following four parameters.

$$Stick\ speed(i) = \frac{StickCmd(i) - StickCmd(i-1)}{\Delta t} \quad \textbf{(4-11)}$$

SpeedMax: largest occurring stick speed per run

SpeedMean: arithmetic mean of all absolute values of stick speed

SpeedRMS: root mean square of all values of stick speed

SpeedRMRatio: quotient of speed root mean square and speed mean

4.4.3 Stick acceleration

Following the same procedure as before (chapter 4.4.2), the sequence for stick acceleration is calculated for every run to provide another four parameters:

$$Stick\ acceleration(i) = \frac{Stick\ speed(i) - Stick\ speed(i-1)}{\Delta t} \quad \textbf{(4-12)}$$

AccMax: largest occurring stick acceleration per run

AccMean: arithmetic mean of all absolute values of stick acceleration

AccRMS: root mean square of all values of stick acceleration

AccRMRatio: quotient of acceleration root mean square and acceleration mean

4.4.4 Error

As already mentioned in chapter 4.2.3 both the sequence of the actual pilot-controlled bank angle Φ_{actual} and the target bank angle Φ_{target} were recorded. The difference between them describes the error:

$$Error(i) = \Phi_{\mathrm{Error}} = \Phi_{\mathrm{target}} - \Phi_{\mathrm{actual}} \quad \textbf{(4-13)}$$

ErrorMean: arithmetic mean of all absolute values of Φ_{Error}

ErrorRMS: root mean square of all values of Φ_{Error}

ErrorRMRatio: quotient of root mean square and mean

4.4.5 Power Spectral Density (PSD)

Besides plotting a sequence over time there is also the opportunity of plotting a sequence over frequency (Power Spectral Density). Figure 4-10 shows this quantitatively: Every bar in in a PSD-plot represents one periodic sequence over time (frequency f = const.).

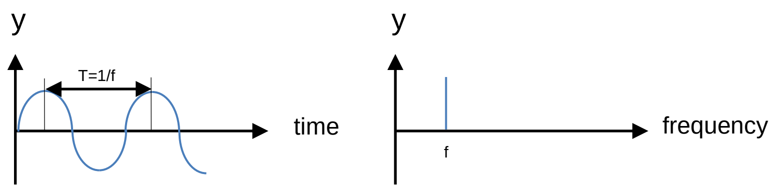


Figure 4-10: Periodic pattern over time (left) and over frequency (right)

By using Fast Fourier Transformation (FFT) in this case the measured *StickCmd* over time can be indicated over frequency showing at which frequencies the pilot's inputs were applied.

The area below the PSD curve (Figure 4-11), reflecting the signal power, is an indicator for pilot control activity [Fie05] . With 2Hz being generally the upper limit of significant frequencies for pilot control inputs [Nie11] , for each run the area below the PSD curve was calculated between 0 and 2Hz (*PSD_Area*).

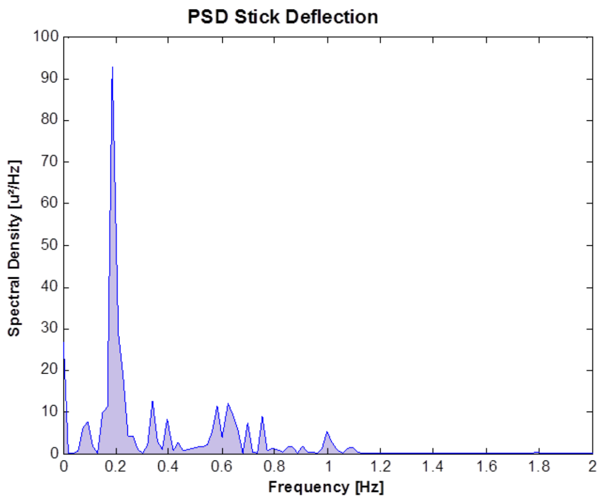


Figure 4-11: Parameter *PSD_Area* as area below the PSD curve between 0 and 2 Hz

4.5 Correlation Analysis

25 parameters that represent possible measures of pilot gain were introduced over the last subchapters. They are again listed in Table 4-3 .

1	AccMax
2	AccMean
3	AccRMRatio
4	AccRMS
5	DeflectionMax
6	DeflectionMean
7	DeflectionRMRatio
8	DeflectionRMS
9	SpeedMax
10	SpeedMean
11	SpeedRMRatio
12	SpeedRMS
13	ErrorMean
14	ErrorRMRatio
15	ErrorRMS
16	PT1_K
17	PT1_TD
18	PT1_TI
19	PT1_Te
20	PT1_QIE
21	PT2_K
22	PT2_Te
23	PT2_QIE
24	CHRating
25	PSD_Area

Table 4-3: 25 parameters for correlation analysis

23 runs were performed in a helicopter simulation. For each run, 25 values for each one of these 25 parameters were obtained.

A correlation matrix was created via correlation analysis of each pair of parameters. No absolute statement about the suitability of the parameters as measures for pilot gain can be made but statement about their relations among each other.

Being the only variation during the test, the differing stick parameters (eigenfrequency and damping) can be considered as chief cause for varying control behaviour.

Table 4-6 indicates the correlation matrix showing the correlations between each possible pair of parameters. The correlation matrix is symmetric because the correlation between parameter x and y is the same as the correlation between y and x. As a parameter's correlation with itself is always equal to 1.00, the diagonal of the matrix is shown greyed out.

Table 4-4 lists the colour code which is utilized in the correlation matrix. The level of significance was set to 0.05, meaning that only correlations including a significance of at least 95% are considered.

Colour	Correlation |R|	Significance p
	≥ 0.7	≤ 0.05
	0.5 ≤ |R| < 0.7	≤ 0.05
	0.3 ≤ |R| < 0.5	≤ 0.05
	< 0.3	> 0.05

Table 4-4: Colour code in correlation matrix

For each possible pair of parameters, data measure for parameter A was plotted against parameter B via MATLAB. Thus, there is one marker per run in each plot. For a significant very high correlation($|R| \geq 0.7, p \leq 0.05$) a trend was included (as well as the linear equation $y = mx + t$ describing it).

The legend utilized in all plots was chosen as follows, depending on command and purpose of each run: A distinction is made between attitude and rate command (AC/RC) and between test and evaluation (T/E). Every stick setting was applied for two runs: at first as test run, afterwards as evaluation.

	AC	RC
Test	★	★
Evaluation	○	○

Table 4-5: Legend applied in correlation plots

	AccMax	AccMean	AccRMRatio	AccRMS	DeflectionMax	DeflectionMean	DeflectionRMRatio	DeflectionRMS	SpeedMax	SpeedMean	SpeedRMRatio	SpeedRMS	ErrorMean	ErrorRMRatio	ErrorRMS	PT1_K	PT1_TD	PT1_TI	PT1_Te	PT1_QIE	PT2_K	PT2_Te	PT2_QIE	CHRating	PSD_Area
AccMax		0.70		0.86					0.85																
AccMean	0.70			0.93						0.92		0.93													
AccRMRatio											0.78														
AccRMS	0.86	0.93							0.82	0.79		0.87													
DeflectionMax						0.72	0.85	0.93							0.79						0.88				0.94
DeflectionMean					0.72			0.86					0.73		0.75					0.75	0.74		0.76		0.87
DeflectionRMRatio					0.85			0.83													0.88				0.80
DeflectionRMS					0.93	0.86	0.83						0.73		0.85						0.96				1.00
SpeedMax	0.85			0.82								0.73													
SpeedMean		0.92		0.79								0.97													
SpeedRMRatio			0.78																					-0.75	
SpeedRMS		0.93		0.87					0.73	0.97															
ErrorMean						0.73		0.73						-0.79	0.92										0.74
ErrorRMRatio													-0.79												
ErrorRMS					0.79	0.75		0.85					0.92								0.72				0.86
PT1_K																	0.89	1.00							
PT1_TD																0.89		0.89							
PT1_TI																1.00	0.89								
PT1_Te																									
PT1_QIE						0.75																	0.85	0.70	0.70
PT2_K					0.88	0.74	0.88	0.96							0.72										0.94
PT2_Te																									
PT2_QIE						0.76														0.85				0.79	
CHRating											-0.75									0.70			0.79		
PSD_Area					0.94	0.87	0.80	1.00					0.74		0.86					0.70	0.94				

Table 4-6: Correlation matrix

4.6 Discussion

The parameters and therefore the correlation matrix are assorted into eight clusters (indicated by fat lines in Table 4-6):

- Stick acceleration
- Deflection
- Stick speed
- Error
- Pilot Model 1
- Pilot Model 2
- Cooper-Harper Rating
- PSD

In the following discussion, in case of no green correlation ($|R| < 0.7$ and $p > 0.05$) for a whole cluster vs. another whole cluster, the individual parameter is no longer considered. In case of significant correlation ($|R| \geq 0.7$ and $p \leq 0.05$) the discussion of the respective individual parameters can be found under the heading of its clusters.

Chapter 4.6.1 includes some discussion about correlations within a cluster (for example SpeedMax vs. SpeedMean) while chapter 4.6.2 concentrates on correlations between different clusters (for example SpeedMax vs. ErrorMean).

4.6.1 Correlations within Clusters

Being only one parameter per cluster, Cooper-Harper Rating and PSD will not be included within this particular discussion.

4.6.1.1 Correlations within Measures of Stick acceleration, Deflection, Stick speed and Error

For each of the four clusters acceleration, deflection, speed and error, there are respectively three measures that are investigated for all of them: Mean, RMS and RMRatio. In addition, for acceleration, deflection and speed, the maximum value Max is examined.

The value for Max is at least equal to Mean and RMS. As Max is only one of the data points Mean and RMS are calculated from, a more exact statement is not possible.

In principle one can say that Mean and RMS, being both ways to calculate an average, are connected. Mean and RMS having the same size is only possible when all measure data, that Mean and RMS are calculated from, are of the same value.

$$RMS \geq Mean \tag{4-14}$$

Moreover with RMRatio being the quotient from RMS and Mean:

$$RMRatio = \frac{RMS}{Mean} \geq 1 \tag{4-15}$$

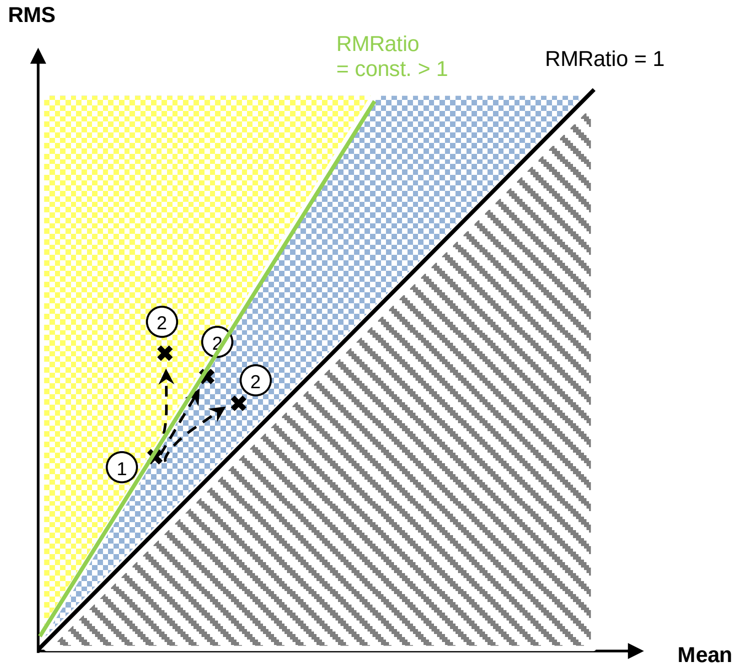


Figure 4-12: Root Mean Square vs. Arithmetic Mean

When plotting RMS vs. Mean (Figure 4-12), the gradient represents RMRatio. Every half-line through origin indicates a correlation RMRatio = const.

Figure 4-12 indicates qualitatively an imaginary run 1 and the different possibilities for RMS and Mean values of an imaginary run 2 ($RMS_{run2} \geq RMS_{run1}$, $Mean_{run2} \geq Mean_{run1}$).

In case of a non-linear correlation between RMS and Mean, if gradient m = RMRatio rises and therefore the curve runs into the yellow area, RMS increases comparatively faster than Mean. If gradient $m = RMRatio$ decreases and therefore the curve runs into the blue area, Mean increases comparatively faster than RMS.

With increasing Mean or RMS, as one can see in Figure 4-13, a positive or negative correlation can then be found vs. RMRatio.

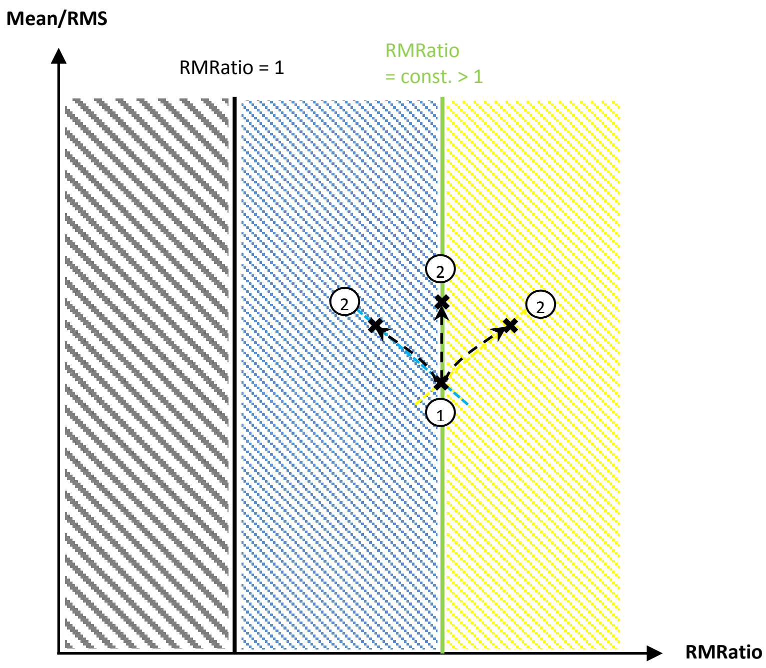


Figure 4-13: RMRatio vs. arithmetic mean or root mean square

What does the development of RMRatio depend on?

	1	2	2/1
x_1	3	**12000**	4000
x_2	4	20000	5000
x_3	5	**28000**	5600
Mean	4	20000	5000
RMS	4.082	**21039.645**	5153.639
RMRatio	1.021	1.052	**1.031**

	1	2	2/1
x_1	3	**15000**	5000
x_2	4	20000	5000
x_3	5	**25000**	5000
Mean	4	20000	5000
RMS	4.082	**20412.415**	5000
RMRatio	1.021	1.021	**1**

	1	2	2/1
x_1	3	**19999**	6666.333
x_2	4	20000	5000
x_3	5	**20001**	4000.200
Mean	4	20000	5000
RMS	4.082	**20000**	4898.979
RMRatio	1.021	1	**0.980**

Table 4-7: Illustrative example for the development of RMRatio with constant mean

For illustration, Table 4-7 indicates three different options for the imaginary run 2. Concrete values were chosen to make the differences more tangible. Mean, RMS and RMRatio are calculated for respectively three values x_1, x_2 and x_3 and two different runs 1 and 2.

In case green RMRatio is constant for an increasing Mean and RMS. This is caused by

$$x_{n,run2} = const * x_{n,run1} \quad \textbf{(4-16)}$$

and leads to

$$\frac{x_{n+1,run2}}{x_{n,run2}} = \frac{x_{n+1,run1}}{x_{n,run1}} \quad \textbf{(4-17)}$$

$$RMRatio, run2 = RMRatio, run1 \quad \textbf{(4-18)}$$

In case blue RMRatio is decreasing for an increasing Mean and RMS. For both runs values for x_1, x_2 and x_3 follow the principles:

$$x_{2,run\,n} = x_{1,run\,n} + const \quad \textbf{(4-19)}$$

$$x_{3,run\,n} = x_{2,run\,n} + const \quad \textbf{(4-20)}$$

As $x_{n,run2} \gg x_{n,run1}$, this leads to

$$\frac{x_{n+1,run2}}{x_{n,run2}} < \frac{x_{n+1,run1}}{x_{n,run1}} \quad \textbf{(4-21)}$$

$$RMRatio, run2 < RMRatio, run1 \quad \textbf{(4-22)}$$

In case yellow, RMRatio is increasing for an increasing Mean and RMS.

$$\frac{x_{n+1,run2}}{x_{n,run2}} > \frac{x_{n+1,run1}}{x_{n,run1}} \quad \textbf{(4-23)}$$

$$RMRatio, run2 > RMRatio, run1 \quad \textbf{(4-24)}$$

After this overview of the mathematic relations, a better understanding of parts of the correlation matrix (Table 4-6) is given and the concrete measure data can be evaluated.

	AccMax	AccMean	AccRMRatio	AccRMS
AccMax		0.70		0.86
AccMean	0.70			0.93
AccRMRatio				
AccRMS	0.86	0.93		

	DeflectionMax	DeflectionMean	DeflectionRMRatio	DeflectionRMS
DeflectionMax		0.72	0.85	0.93
DeflectionMean	0.72			0.86
DeflectionRMRatio	0.85			0.83
DeflectionRMS	0.93	0.86	0.83	

	SpeedMax	SpeedMean	SpeedRMRatio	SpeedRMS
SpeedMax				0.73
SpeedMean				0.97
SpeedRMRatio				
SpeedRMS	0.73	0.97		

	ErrorMean	ErrorRMRatio	ErrorRMS
ErrorMean		-0.79	0.92
ErrorRMRatio	-0.79		
ErrorRMS	0.92		

Table 4-8: Correlation within clusters: stick acceleration, stick speed, deflection, error

It is noticeable that the proportionately biggest part of significant correlations can be found within the clusters error and deflection and only few within speed and acceleration.

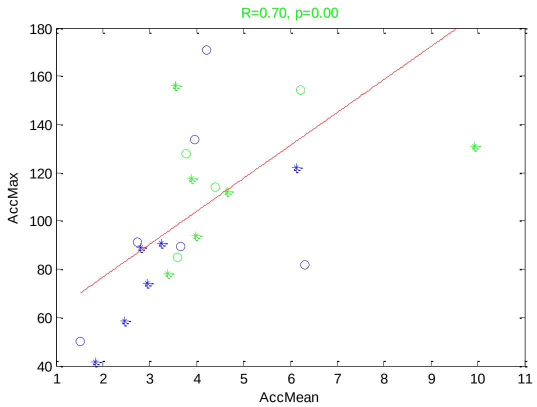
Mean and RMS show a very good correlation for all four clusters, especially for speed, with higher values for RMS than for Mean, as expected.

Max correlates very well with RMS, but only for deflection also shows high correlation with Mean. This reflects the fact that peaks have a stronger impact on RMS than on Mean and RMS is the better indicator for strong deviations from a trend.

Deflection is also the only cluster showing a correlation between Max and RMS, Mean and RMRatio. An increasing RMRatio here indicates the fact that RMS is growing faster than Mean.

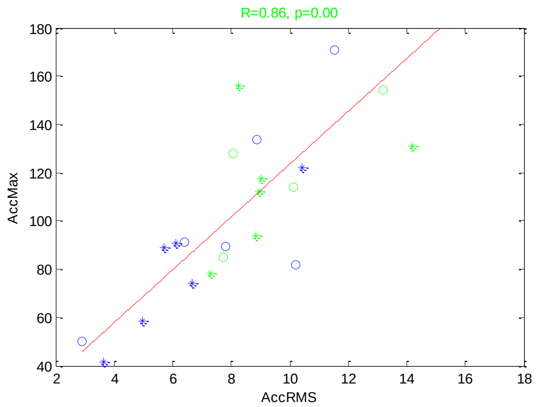
Almost always the significant correlations are positive which means that if one parameter increases the other one does, too. Yet in some cases like Mean vs. RMSRatio an increasing Mean leads to a decreasing RMRatio. This can be observed for ErrorMean vs. ErrorRMRatio.

As discussed earlier, this inverse correlation could reflect that the deviations from an ErrorMean did not grow in the same manners as the ErrorMean itself.



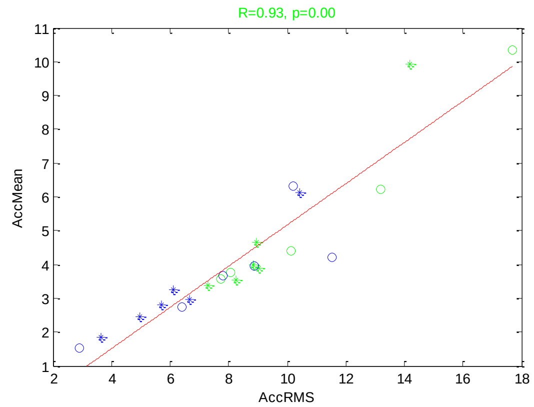
Trend: y = 13.65x + (49.31)

Figure 4-15: AccMax vs. AccMean



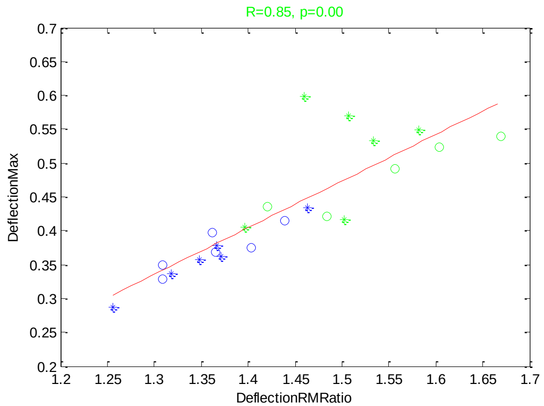
Trend: y = 10.95x + (13.91)

Figure 4-14: AccMax vs. AccRMS



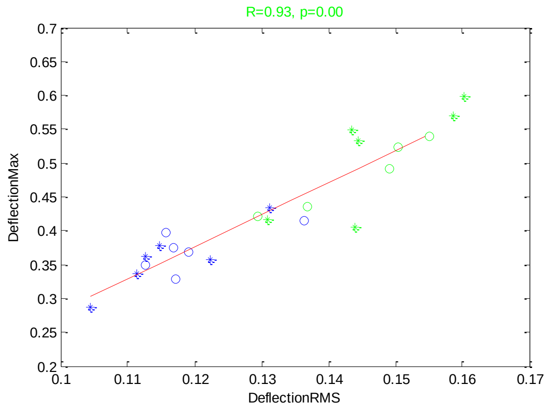
Trend: y = 0.61x + (-0.94)

Figure 4-16: AccMean vs. AccRMS



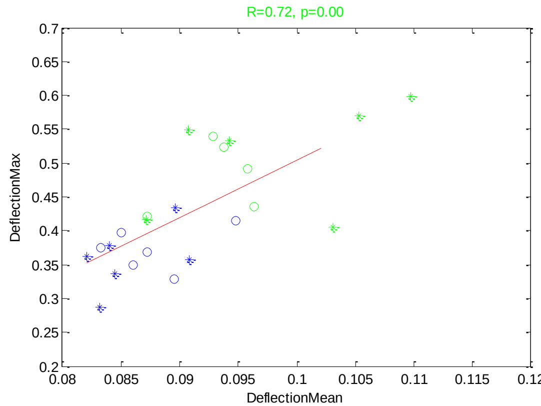
Trend: y = 0.69x + (-0.56)

Figure 4-19: DeflectionMax vs. DeflectionRMRatio



Trend: y = 4.74x + (-0.19)

Figure 4-18: DeflectionMax vs. DeflectionRMS



Trend: y = 8.48x + (-0.34)

Figure 4-17: DeflectionMax vs. DeflectionMean

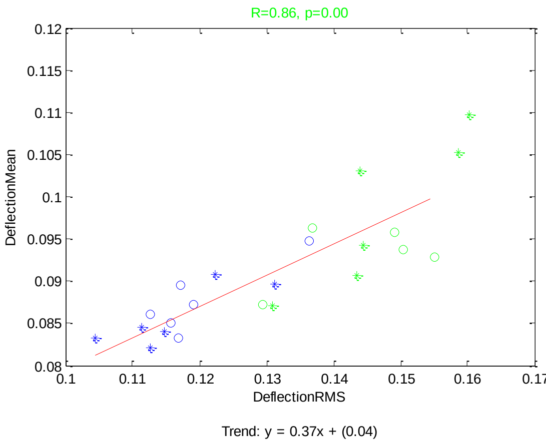


Figure 4-22: DeflectionMean vs. DeflectionRMS

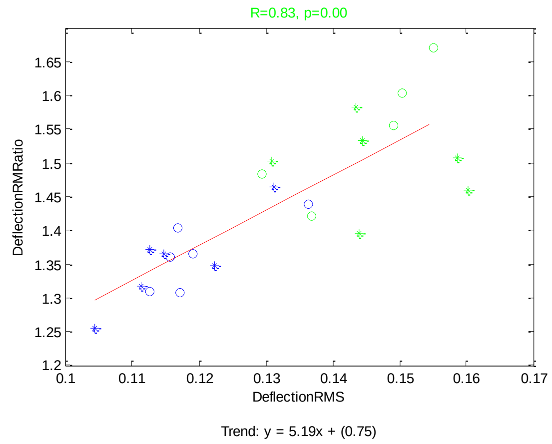


Figure 4-21: DeflectionRMRatio vs. DeflectionRMS

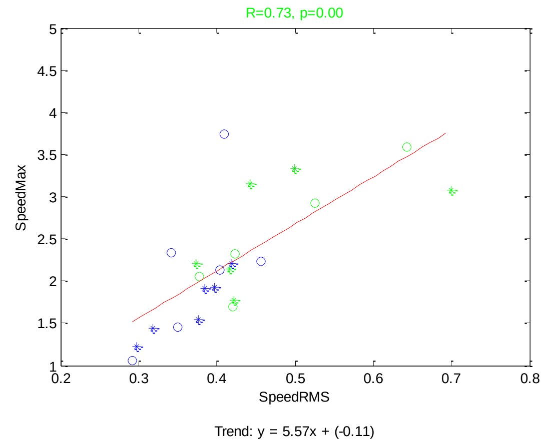


Figure 4-20: SpeedMax vs. SpeedRMS

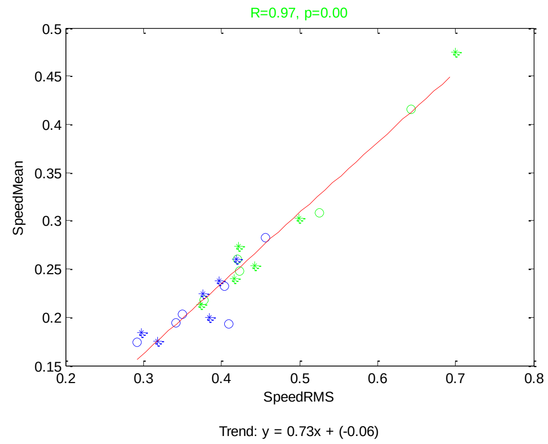


Figure 4-25: SpeedMean vs. SpeedRMS

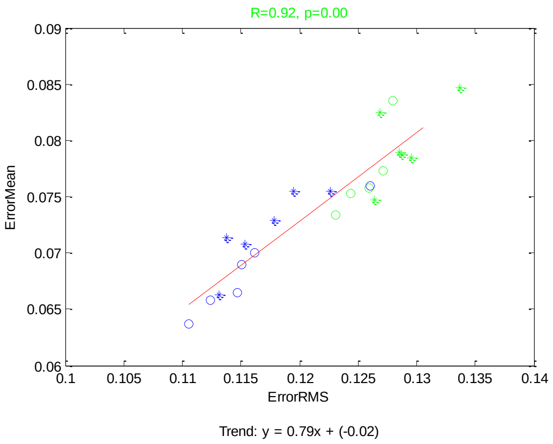


Figure 4-24: ErrorMean vs. ErrorRMS

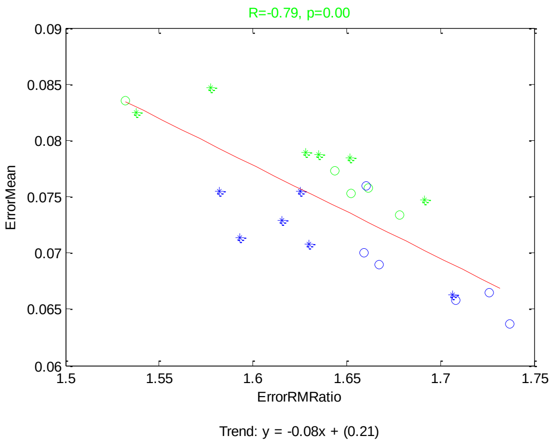


Figure 4-23: ErrorMean vs. ErrorRMRatio

Though not being as clear as the correlation between ErrorMean and ErrorRMRation, DeflectionMean vs. DeflectionRMRatio show a relevance R > 0. So in this case the correlation would mean that with increasing deflections the variation of deflections slightly increases as well.

In general it can be observed that data from RC (green) tends to show higher values than AC (blue). This phenomenon is discussed in chapter 4.6.3.

4.6.1.2 Correlations within Parameters of Pilot Model 1

	PT1_K	PT1_TD	PT1_TI	PT1_Te	PT1_QIE
PT1_K		0.89	1.00		
PT1_TD	0.89		0.89		
PT1_TI	1.00	0.89			
PT1_Te					
PT1_QIE					

Table 4-9: Correlation within cluster Pilot Model 1

Values for pilot model parameters were calculated by the parameter identification software FITLAB. The result is an optimization for each of the five parameters.

During the examination of the resulting correlations and the associated plots, it stood out that the parameter values for two runs were extremely higher than others. Figure 4-26 shows an example. A linear correlation here has only been created because all values, except the outliers, show little variance towards each other. Thus the outliers and the cloud of remaining values are connected by MATLAB by a linear trend.

A closer look showed that the outliers were a result from the parameter identification not working in this particular case.

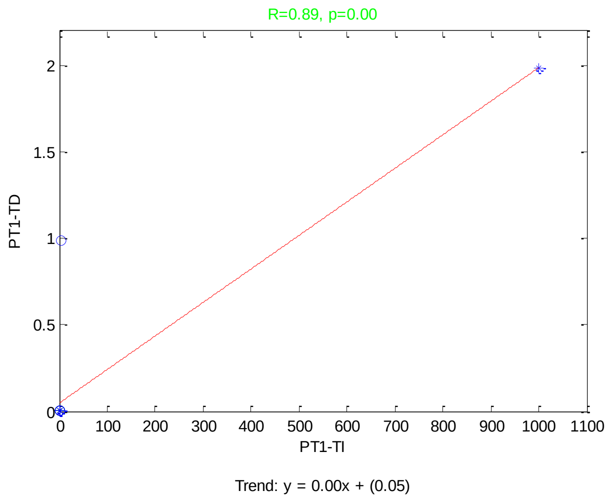


Figure 4-26: PT1-TD vs. PT1-TI

After excluding these 2 runs and repeating calculating the correlations for all parameters of pilot model 1, the result is shown by Table 4-10 and exemplarily Figure 4-27: no significant correlation towards other parameters within this cluster. This result indicates that without the now excluded outliers, no high and significant correlations exist.

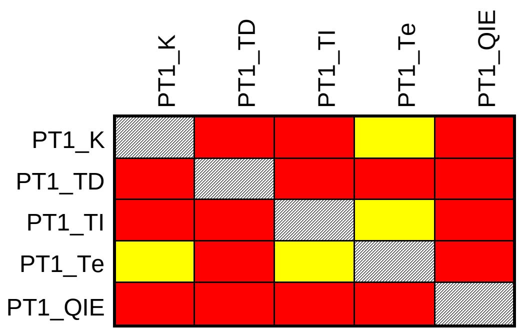


Table 4-10: Correlation within cluster Pilot Model 1 (after excluding 2 runs)

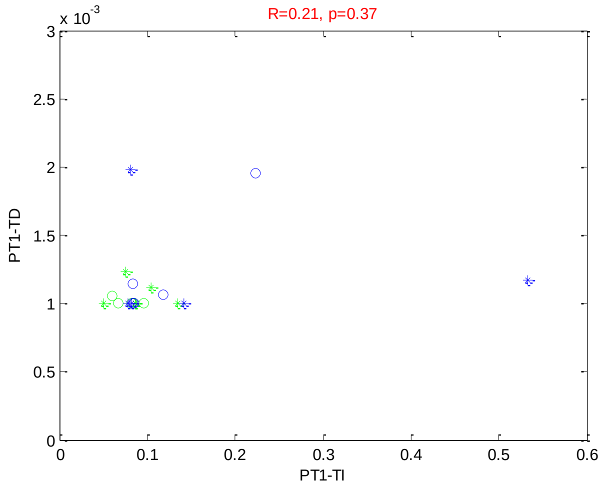


Figure 4-27: PT1-TD vs. PT1-TI (after excluding 2 runs)

4.6.1.3 Correlations within Parameters of Pilot Model 2

No significant correlation $|R| \geq 0.7$ was found.

4.6.2 Correlations between Different Clusters

4.6.2.1 Stick acceleration vs. Stick speed

	SpeedMax	SpeedMean	SpeedRMRatio	SpeedRMS
AccMax	0.85			
AccMean		0.92		0.93
AccRMRatio			0.78	
AccRMS	0.82	0.79		0.87

Table 4-11: Stick acceleration vs. stick speed

Correlations between speed and acceleration (see Figure 4-28 to Figure 4-31) are not surprising. Although the pilot and the tracking task stay the same for every run, the differing stick settings allow once higher, once lower speed and acceleration. If for example the damping is rather small, higher speed and acceleration are possible.

Due to the changes within the tracking task, there is a strong variation in speed values and, as acceleration represents speed changes, acceleration values during every run.

The correlation between AccMean/RMS and SpeedMax confirms this: As the tracking task asks for changes in deflection and therefore changes in speed, an increasing building up and down in speed leads to increasing accelerations.

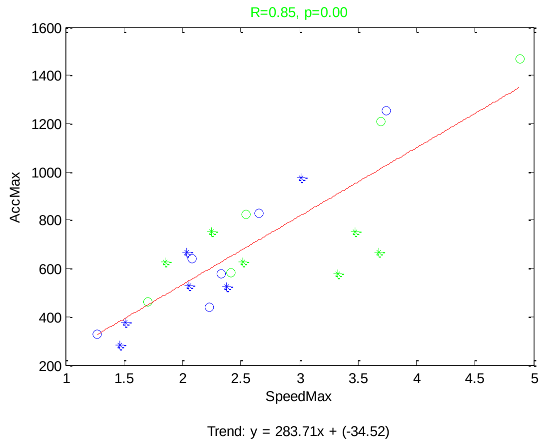


Figure 4-30: AccMax vs. SpeedMax

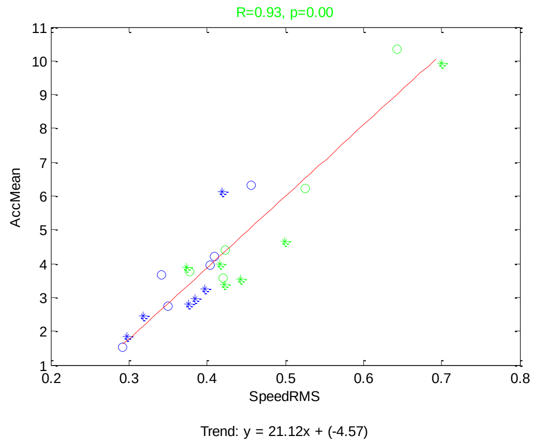


Figure 4-29: AccMean vs. SpeedRMS

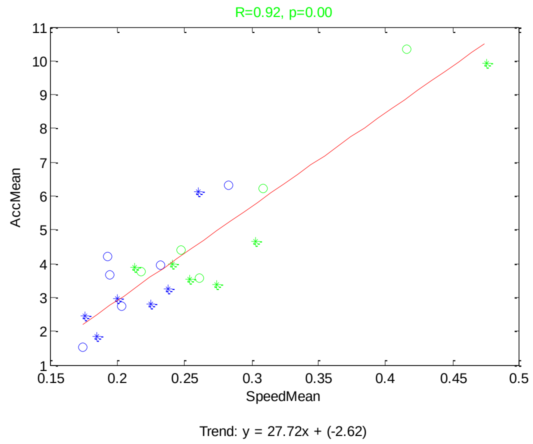


Figure 4-28: AccMean vs. SpeedMean

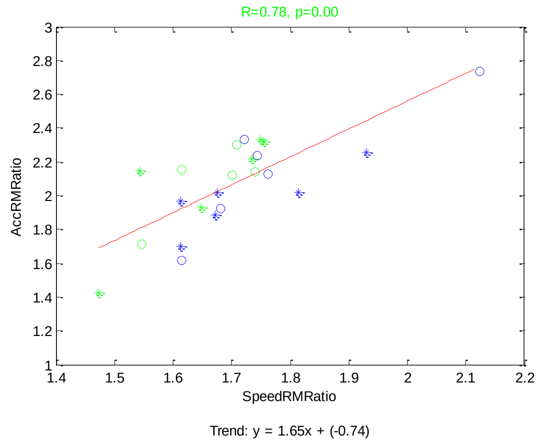


Figure 4-33: AccRMRatio vs. SpeedRMRatio

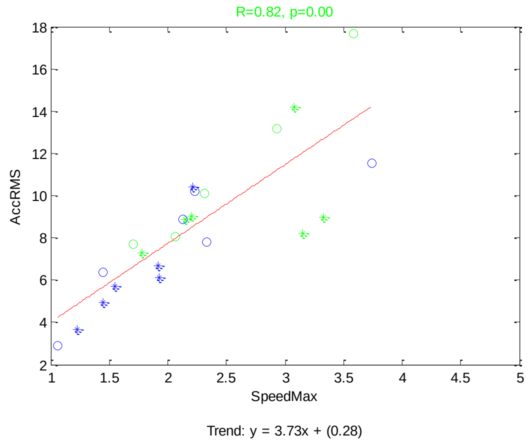


Figure 4-32: AccRMS vs. SpeedMax

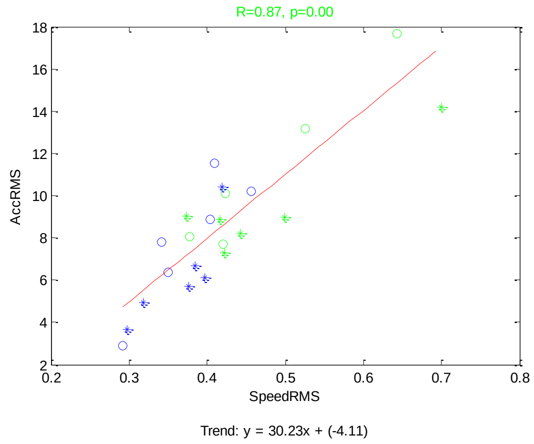


Figure 4-31: AccRMS vs. SpeedRMS

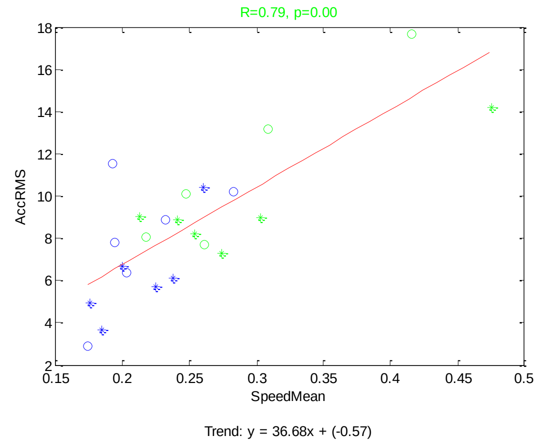


Figure 4-36: AccRMS vs. SpeedMean

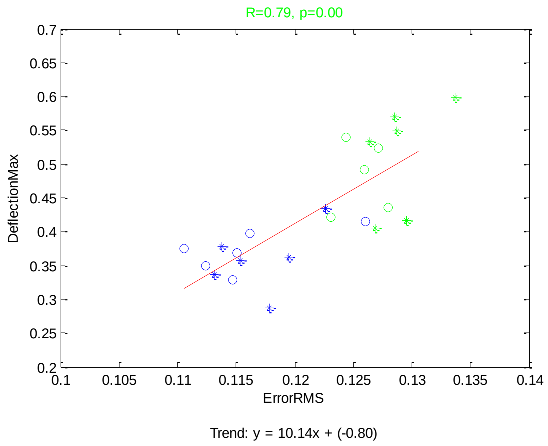


Figure 4-35: DeflectionMax vs. ErrorRMS

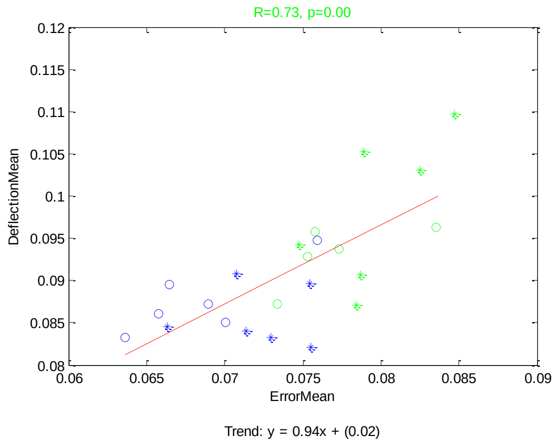


Figure 4-34: DeflectionMean vs. ErrorMean

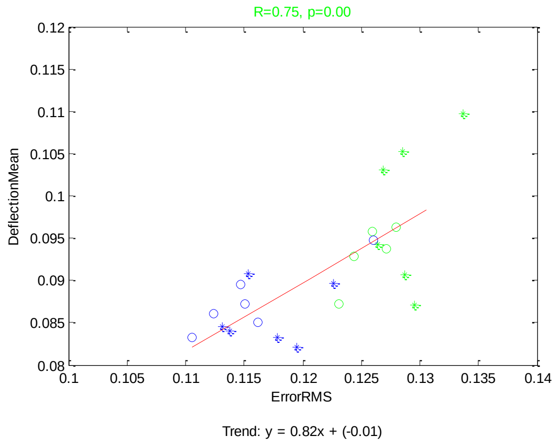


Figure 4-39: DeflectionMean vs. ErrorRMS

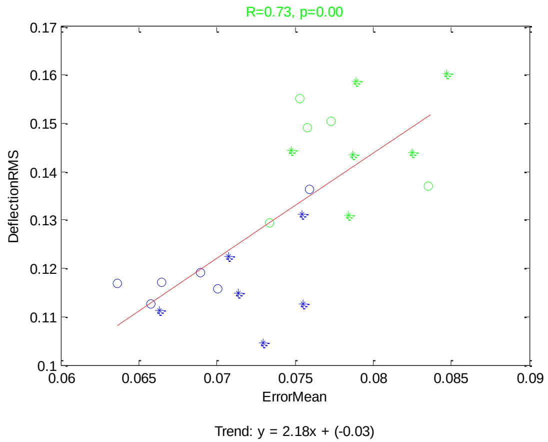


Figure 4-38: DeflectionRMS vs. ErrorMean

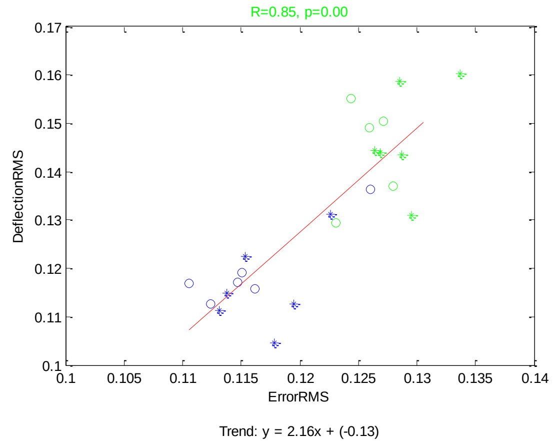


Figure 4-37: DeflectionRMS vs. ErrorRMS

4.6.2.2 Deflection vs. Error

	ErrorMean	ErrorRMRatio	ErrorRMS
DeflectionMax			0.79
DeflectionMean	0.73		0.75
DeflectionRMRatio			
DeflectionRMS	0.73		0.85

Table 4-12: Deflection vs. error

There are several significant positive correlations between deflection and error.

It is noticeable for all plots that the variation is rather large and therefore most values are not close to the trend. Moreover it seems as if the existence of the linear trend is mainly supported by AC values being smaller than RC values. Within AC and RC no clear trend can be observed.

The main statement of these plots: deflection and error values are both larger in RC than in AC (also see chapter 4.6.3).

4.6.2.3 Deflection vs. Pilot Model 1

After excluding two runs (see chapter 4.6.1.2), there are three correlations between deflection and Pilot Model 1:

	DeflectionMax	DeflectionMean	DeflectionRMRatio	DeflectionRMS
PT1_K	0.75			0.79
PT1_TD				
PT1_TI				
PT1_Te				
PT1_QIE		0.80		

Table 4-13: Deflection vs. pilot model 1 (after excluding 2 runs)

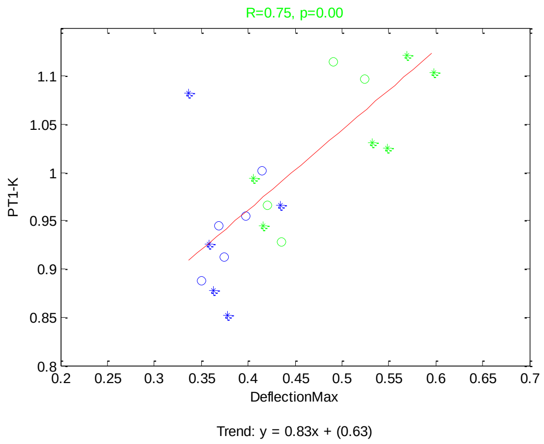


Figure 4-42: PT1-K vs. DeflectionMax

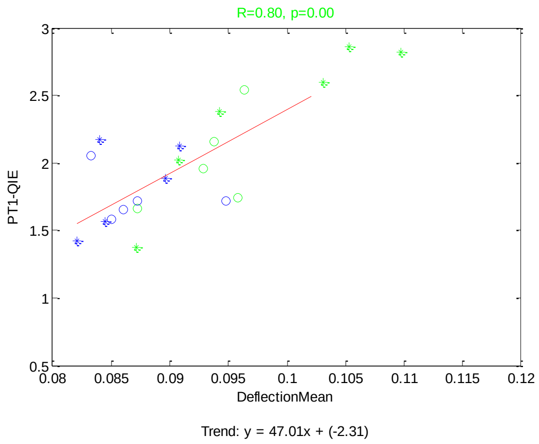


Figure 4-41: PT1-QIE vs. DeflectionMean

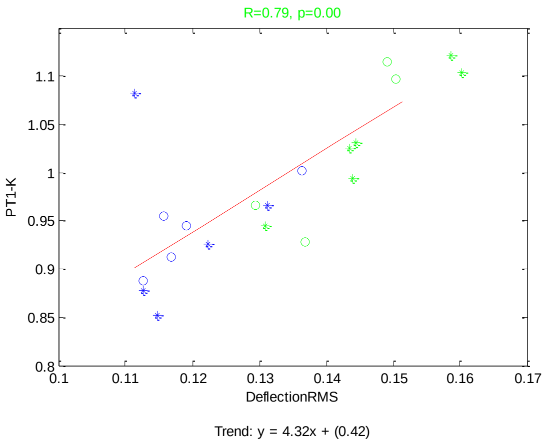


Figure 4-40: PT1-K vs. DeflectionRMS

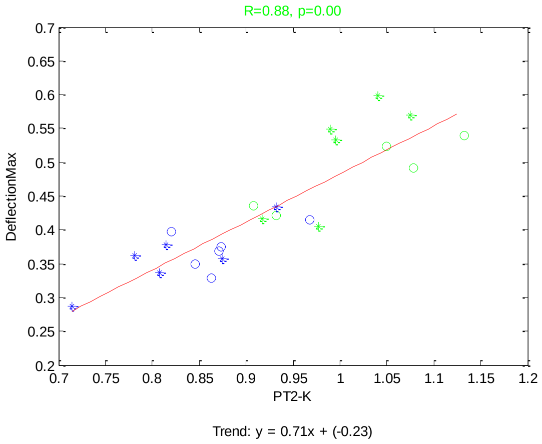


Figure 4-45: DeflectionMax vs. PT2-K

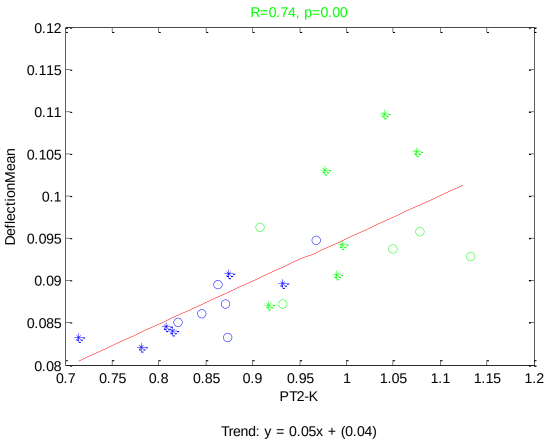


Figure 4-44: DeflectionMean vs. PT2-K

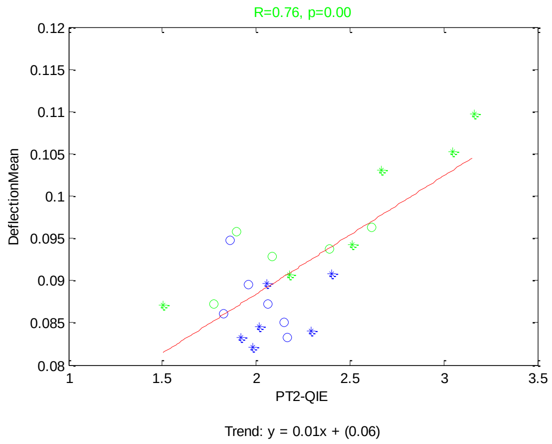


Figure 4-43: DeflectionMean vs. PT2-QIE

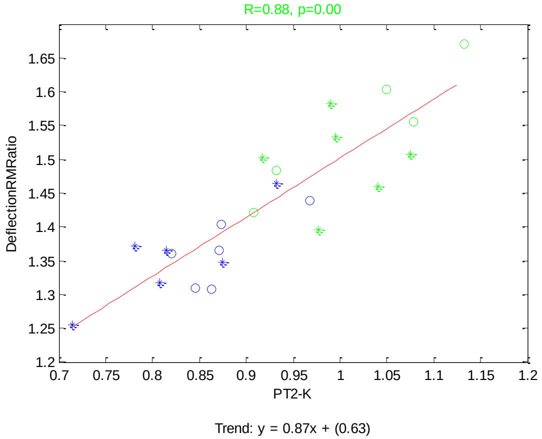


Figure 4-47: DeflectionRMRatio vs. PT2-K

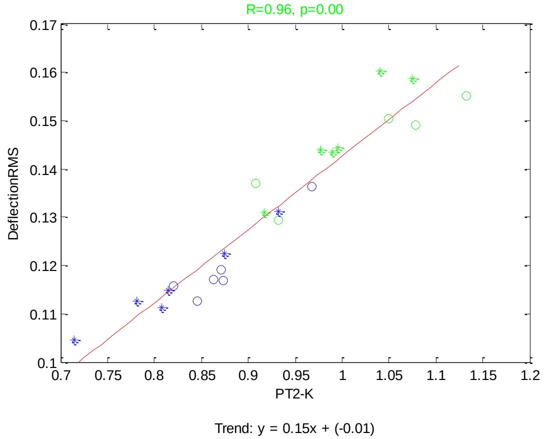


Figure 4-46: DeflectionRMS vs. PT2-K

The pilot model gain PT1_K correlates significantly with DeflectionMax and DeflectionRMS.

The pilot model parameters were optimized by FITLAB in a way that the actual sequence of pilot inputs is reflected as well as possible. As PT1_K is the main contributor to the amplitude of the tracking task a correlation with DeflectionMax is comprehensible.

Moreover there is a high correlation between PT1_QIE and DeflectionMean. PT1_QIE represents how well the paramter identification was able to simulate the pilot's input. The bigger this value, the worse is the model fit. Thus, the correlation indicates that the bigger the average deflection, the worse the model fit.

One possible reason for this correlation could be that the increasing DeflectionMean is caused by an increasing amount of large peaks in stick deflection the pilot model is not able to regard.

4.6.2.4 Deflection vs. Pilot Model 2

	PT2_K	PT2_Te	PT2_QIE
DeflectionMax	0.88		
DeflectionMean	0.74		0.76
DeflectionRMRatio	0.88		
DeflectionRMS	0.96		

Table 4-14: Deflection vs. pilot model 2

Whilst for pilot model 1 PT1_TD and PT1_TE also contribute to simulating the amplitude of a sequence, pilot model 2 only consists of a time delay and pilot model gain. PT2_K has an ever better correlation with deflection especially DeflectionRMS.

The significant correlation DeflectionMean vs. PT2_QIE can be explained in accordance with DeflectionMean vs. PT2_QIE (see chapter 4.6.2.3).

4.6.2.5 *Stick speed vs. Cooper-Harper Rating*

	CHRating
SpeedMax	
SpeedMean	
SpeedRMRatio	-0.75
SpeedRMS	

Table 4-15: Stick speed vs. Cooper-Harper Rating

Correlations including the Cooper-Harper Rating are built of only eleven measure point within this thesis (only evaluation-runs were rated). That is why resulting correlations have to be looked at even more carefully than others.

SpeedRMRatio shows a significant inverse correlation vs. Cooper-Harper Rating (Figure 4-48). The Cooper-Harper Rating is the pilot's subjective evaluation of how he was able to handle the tracking task at different stick settings. The lower the rating, the higher is the pilot's satisfaction.

For the correlation this means, the higher SpeedRMRatio, the more satisfied the pilot. An increasing SpeedRMRatio represents a growing variation in the values, Mean, RMS and therefore RMRatio are calculated from. Possibly the stick settings allowed a high variation of stick speed that was evaluated positively by the pilot.

However it cannot be ruled out that the correlation is only coincident.

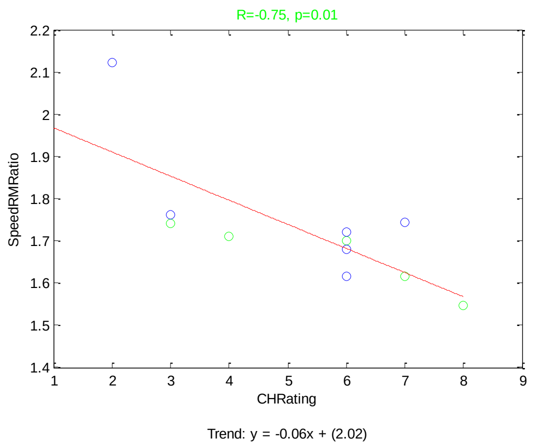


Figure 4-48: SpeedRMRatio vs. CHRating

4.6.2.6 Deflection vs. PSD

Table 4-16 shows that all measures of deflection correlate highly with PSD_Area. Other than all other measures, PSD_Area is a measure in the frequency domain.

In Figure 4-49 one can see the frequency distribution of the actual task between 0 and 2 Hz. There are two very dominating frequencies at about 0.1 Hz and 0.2 Hz and two rather small ones at 0.6 Hz and 1Hz.

All other frequency peaks than those shown in Figure 4-49 are self-induced by the pilot.

	PSD_Area
DeflectionMax	0.94
DeflectionMean	0.87
DeflectionRMRatio	0.80
DeflectionRMS	1.00

Table 4-16: Deflection vs. PSD

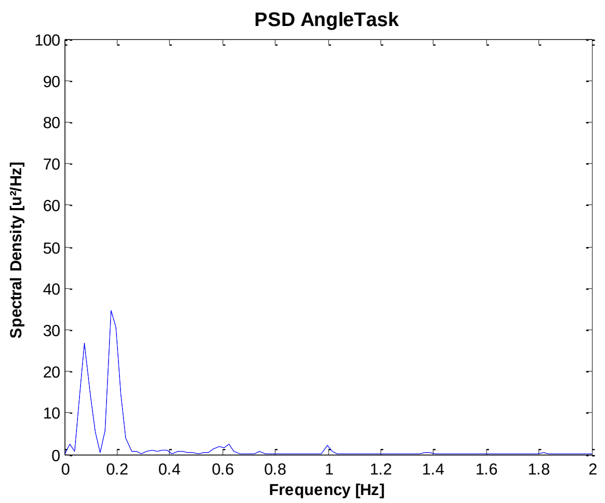


Figure 4-49: Power Spectral Density of Roll Tracking Task

Figure 4-50 is included as an example for PSDs for two different runs but same stick settings (PSD_Area for run 006 (rate command(RC)): 6.0513, PSD_Area for run 016 (attitude command (AC)): 3.4689).

It can be seen that the dominating frequencies are those evoked by the tracking task itself (Figure 4-49). In rate command the peaks at 0.2 Hz and 0.6 Hz are significantly higher than in attitude command. Moreover the area under the actual sequence, PSD_Area, is almost twice as large.

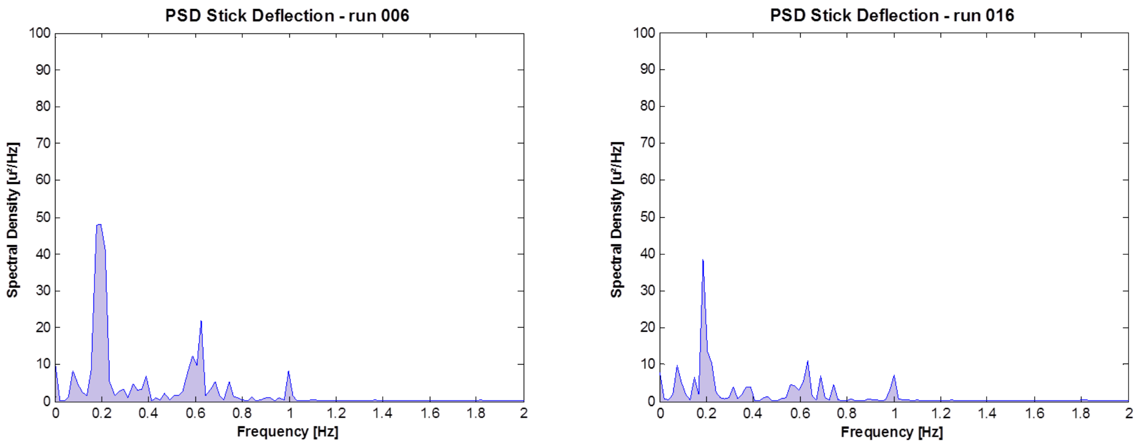


Figure 4-50: PSD Stick Deflection for run 006 (RC) and run 016 (AC)

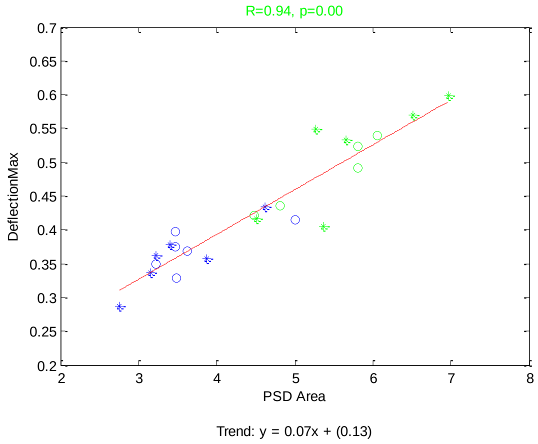


Figure 4-53: DeflectionMax vs. PSD_Area

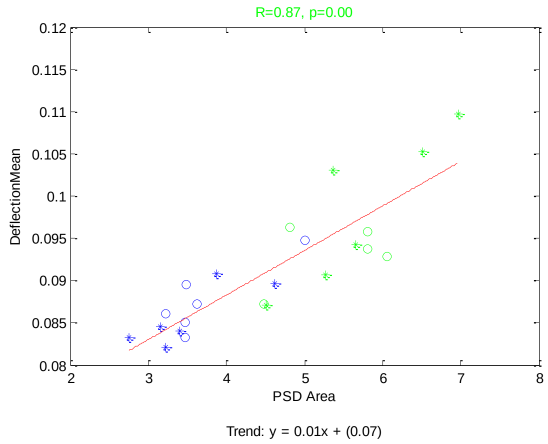


Figure 4-52: DeflectionMean vs. PSD_Area

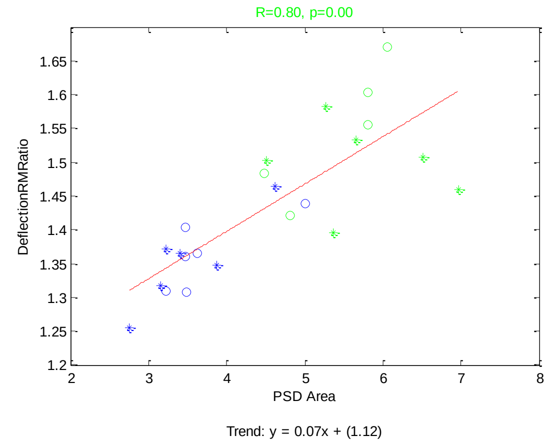


Figure 4-51: DeflectionRMRatio vs. PSD_Area

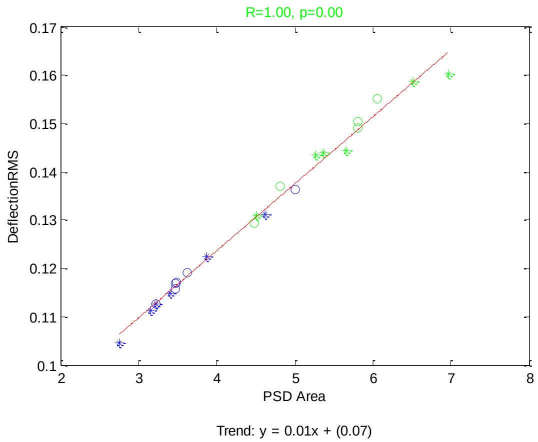


Figure 4-56: DeflectionRMS vs. PSD_Area

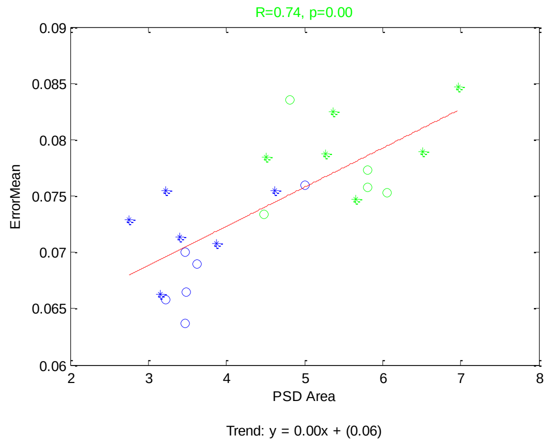


Figure 4-55: ErrorMean vs. PSD_Area

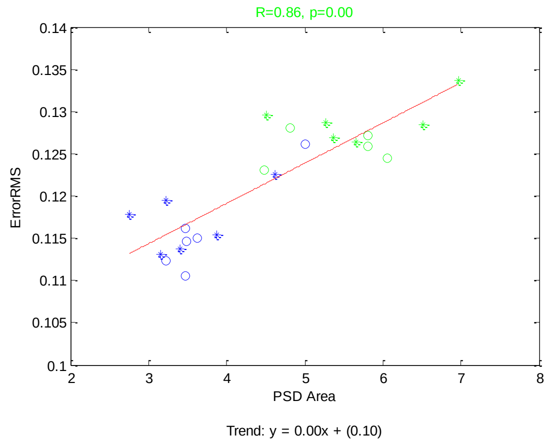


Figure 4-54: ErrorRMS vs. PSD_Area

The strong correlations show that the area below the PSD grows proportionally with increasing deflection. Especially for DeflectionRMS, an almost perfect correlation can be obtained. Again, the differences for values in RC and AC support the linear trend.

PSD_Area grows with growing input in the stick. Other than a PSD-plot, PSD_Area does not give any information at which frequency the inputs were made and if the highest inputs were made at the target frequencies or any other between 0 and 2 Hz. As RMS is calculated by deflections by square this highest correlation DeflectionRMS vs. PSD_Area can be explained.

4.6.2.7 Error vs. PSD

	PSD_Area
ErrorMean	0.74
ErrorRMRatio	
ErrorRMS	0.86

Table 4-17: Error vs. PSD

Error correlates indirectly with PSD (Figure 4-55 and Figure 4-54). With DeflectionMean and Deflection RMS highly correlating with ErrorMean and ErrorRMS, PSD_Area also grows with growing Error.

4.6.2.8 Error vs. Pilot Model 2

	PT2_K	PT2_Te	PT2_QIE
ErrorMean			
ErrorRMRatio			
ErrorRMS	0.72		

Table 4-18: Error vs. pilot model 2

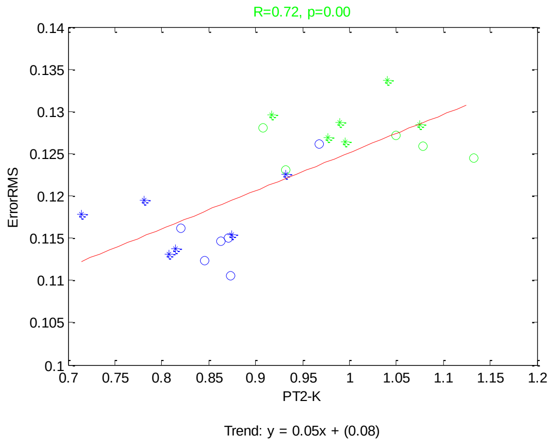


Figure 4-57: ErrorRMS vs. PT2-K

ErrorRMS vs. PT2_K is another example for a correlation being highly supported by values for RC being higher than values for AC. There is still a high and negative correlation within AC and RC.

Possibly the correlation can be derived by PT2_K correlating well with DeflectionRMS and DeflectionRMS correlating with ErrorRMS which would represent an indirect correlation. There is definitely no possibility for PT2_K to react on bank angle errors.

4.6.2.9 Pilot Model 1 vs. Pilot Model 2

	PT2_K	PT2_Te	PT2_QIE
PT1_K	0.83		
PT1_TD			
PT1_TI			
PT1_Te			
PT1_QIE			0.94

Table 4-19: Pilot model 1 vs. pilot model 2

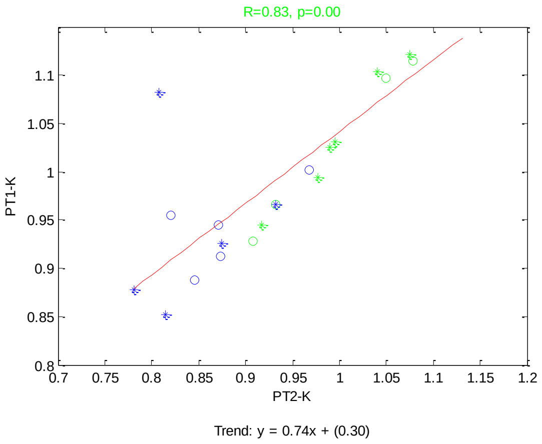


Figure 4-58: PT1_K vs. PT2_K

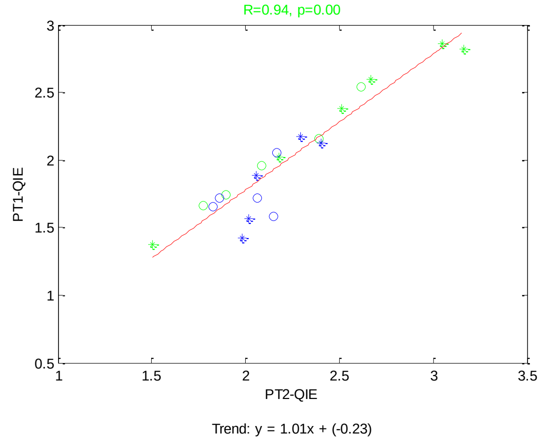


Figure 4-59: PT1_QIE vs. PT2_QIE

PT2_K correlates highly with PT1_K most of the time (Figure 4-58).

A very high correlation can be found between PT1_QIE and PT2_QIE. Thus, runs which can be simulated well by pilot model 1, can also be simulated well by pilot model 2.

No further high correlations can be found.

4.6.2.10 Pilot Model 2 vs. Cooper-Harper Rating

	CHRating
PT2_K	
PT2_Te	
PT2_QIE	0.79

Table 4-20: Pilot model 2 vs. Cooper-Harper Rating

There is no physical or mathematical relationship between the Cooper-Harper Ratings and PT2_QIE. The only possibility one could think of, is that there is an indirect connection behind, like the pilot preferring a stick setting which leads to a pilot input that can be easily followed by the pilot model.

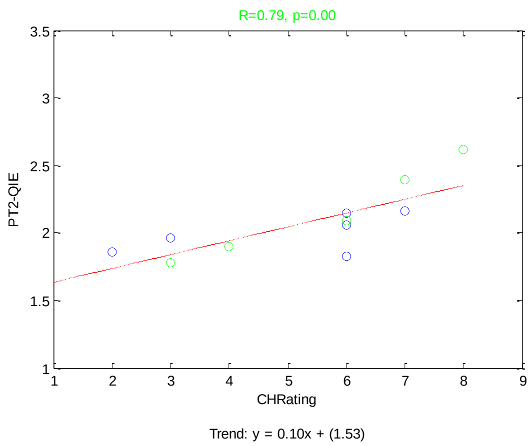


Figure 4-60: PT2_QIE vs. CHRating

4.6.2.11 Pilot Model 1 and 2 vs. PSD

	PSD_Area
PT2_K	0.94
PT2_Te	
PT2_QIE	

	PSD_Area
PT1_K	0.78
PT1_TD	
PT1_TI	
PT1_Te	
PT1_QIE	

Table 4-21: Pilot model 1 (after excluding 2 runs) and pilot model 2 vs. PSD

Pilot Model 1 and 2 vs. PSD show consistent correlations: As PT1_K and PT2_K as well as PT1_QIE and PT2_QIE correlate very well with each other, they show the same behaviour towards PSD_Area.

As already discussed earlier PT1_K and PT2_K mainly represent the amplitude of tracking behaviour and correlate well with deflection measures. With an increasing average deflection, the signal power increases and consequently PSD_Area does so, too.

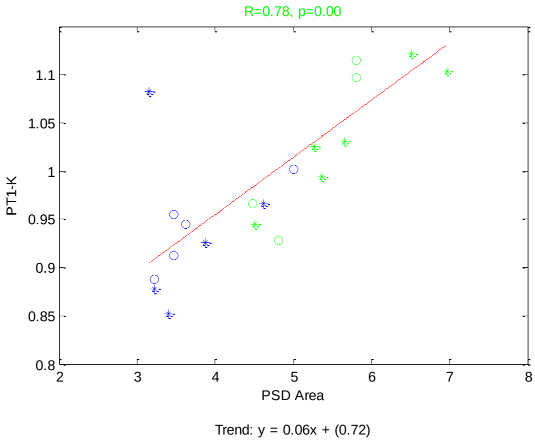


Figure 4-61: PT1_K vs. PSD_Area

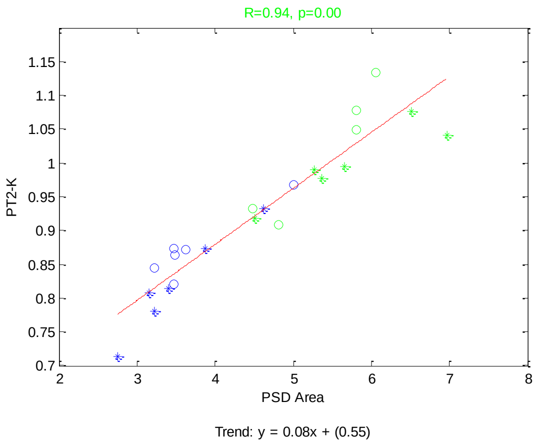


Figure 4-62: PT2_K vs. PSD_Area

4.6.2.12 Stick speed vs. PSD

There are no highly significant correlations between Stick speed and PSD.

SpeedRMS vs. PSD_Area (Figure 4-63) is described by a correlation R = 0.47, being mainly caused by values in RC being larger than values in AC. Within AC or RC, no clear trend is visible.

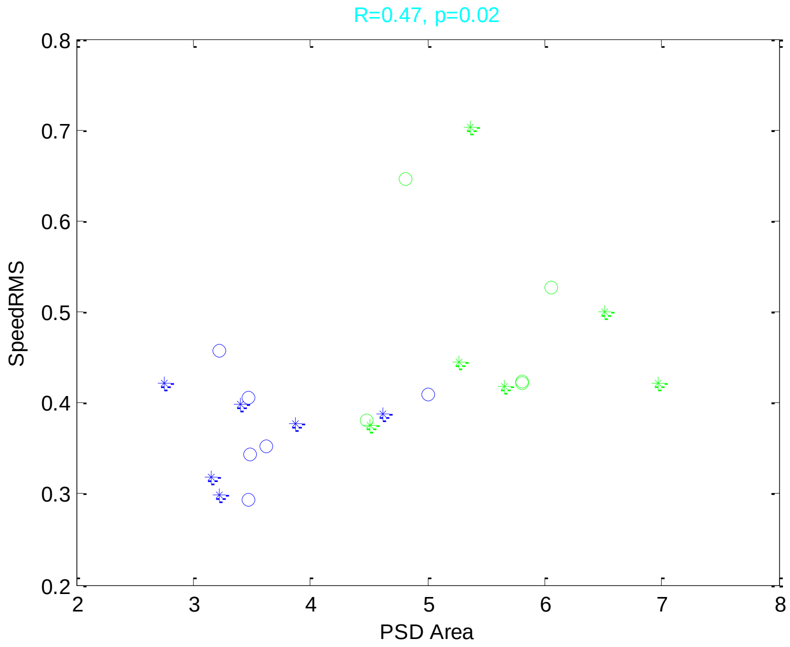


Figure 4-63: SpeedRMS vs. PSD_Area

In contrast, in an on-going test campaign on measures of pilot gain [Nie12, not yet published], a clear (linear) trend can be observed for SpeedRMS vs. PSD_Area (Figure 4-64).

Moreover completely different values can be observed for SpeedRMS and the range of PSD_Area.

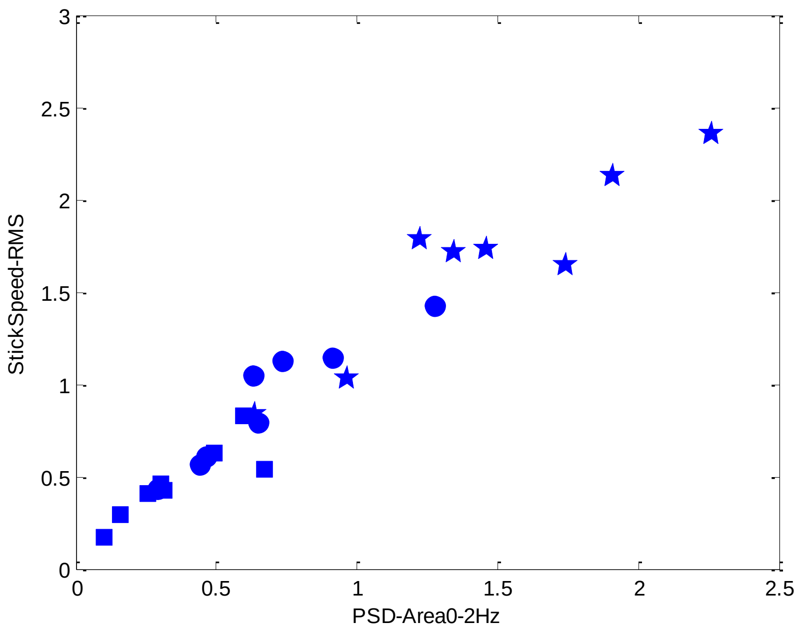


Figure 4-64: StickSpeed-RMS vs. PSD-Area0-2Hz [Niewind 2012, not yet published]

To figure out why there are these differences and why there is no clear correlation within this thesis, the differences between the two different test situations has to be observed. What are the conditions Figure 4-64 results from?

Measure data for eight pilots are included in Figure 4-64. Their task was to follow a pitch tracking task four times: once applying low gain (squares in Figure 4-64), once high gain (stars in Figure 4-64) and once applying normal gain (dots in Figure 4-64). The forcing function was created as a SOS with eight different frequencies.

Fixed wing aircraft simulation instead of helicopter simulation

Flying a helicopter is different to flying an aircraft. For each task (fixed wing and helicopter) the pilots that were chosen had a background and experience for the respective aircraft which results in different control strategies.

Typically, for helicopters there is a stronger coupling between the body axes. It was tried to minimize this effect by setting the target bank angle to values below +/-10°.

The forcing function describing the tracking task was originally created for fixed wing aircraft. As preparation for the study, it was adapted to make it a helicopter task [Non10]

SOS task instead of DTT

The control strategy during an SOS task is different to the one of a DTT. Other than with a constantly changing target value, where one tries to follow as closely as possible (SOS task), the control strategy for DTT also includes phases of holding the target value.

Moreover in the DTT, there are phases when the target value changes which would theoretically ask for an infinite stick speed to follow perfectly.

Pitch tracking task instead of roll tracking task

Different directions of hand and arm movements are required.

Pursuit display instead of compensatory display

On a pursuit display, both target and actual values are displayed, the pilot has to “calculate” the error value himself and concentrates on following the target value. The compensatory display only shows the current error the pilot tries to minimize.

In the author’s opinion, the following two points make the most tremendous difference:

No variation in stick settings

During the helicopter tracking task several settings of stick damping and stick eigenfrequency were tried. The pilot’s tracking strategy had to vary for every evaluation and the stick settings did not allow the same tracking accuracy or behaviour.

In terms of individual gain, if a stick setting A allowed faster deflections than stick setting B, and therefore for example the pilot gain measure DeflectionMax increases, it does not necessarily allow the consequence that the pilot increased his gain.

More than one pilot

Other than in the helicopter simulator study, Niewind's results are the measure data and therefore the tracking strategies of eight different pilots with very different backgrounds. Possibly, measure data of a second helicopter pilot in the simulator would support correlations or bring out correlations where there is none at the momentary state of results.

Different assignments of tasks

A comparison between the pilots is also hindered by the different assignments of tasks. While the helicopter pilot was trying to do the task as good as possible and was concentrating on evaluating the varying stick settings, the pilot gain campaign-pilots had to perform a task utilizing their individual conception of high, medium and low gain.

As the helicopter pilot was not told to intentionally apply high, normal or low gain, it is not possible to say whether he changed his gain over the runs, what kind of gain he applied and what part of his natural bandwidth was covered.

As discussed in chapter 4.6.2.6 there is an extremely high correlation between DeflectionRMS and PSD_Area. If there was a high correlation between DeflectionRMS and SpeedRMS, the result would be a higher correlation between SpeedRMS and PSD_Area and rather be in line with Niewind's results. This missing link between measures of deflection and speed could possibly be a result of failures in stick speed calculation and has to be investigated.

4.6.3 Attitude Command vs. Rate Command

As presented in chapter 4.2 two different command modes have been utilized to gain measuring data: Rate Command (RC) and Attitude Command (AC). Whilst the helicopter in RC responds to a stick deflection δ with a proportional roll rate, in AC the same stick deflection result in a proportionally steady state attitude. Figure 4-65 indicates an example for how the stick deflection in RC and AC would look like for performing the same roll tracking task Φ, already including a small time delay caused by the pilot and system.

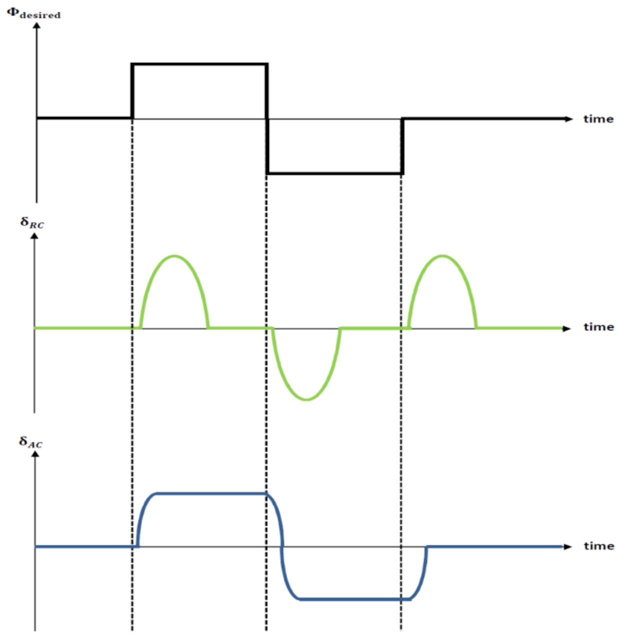


Figure 4-65: Comparison of stick deflections in different command modes to perform the same task [Non10]

Six different runs were chosen to compare RC and AC. Thus, it is three pairs with the same stick settings that can be compared among each other (see Table 4-22). The pilot’s opinion on the stick settings of every pair was quite similar.

Run	Command	Purpose	ω_s [Hz]	k [N/deg]	D [-]
6	RC	E	3.0	2.0	1.1
16	AC	E	3.0	2.0	1.1
10	RC	E	3.0	2.0	1.5
20	AC	E	3.0	2.0	1.5
14	RC	E	4.0	2.0	1.1
24	AC	E	4.0	2.0	1.1

Table 4-22: Selection of runs for comparison

On the following pages, two plots for each run are included, one showing the stick deflection *StickCmd* over time as input on the stick, the other showing the actual pilot-controlled bank angle as output. For all plots the target bank angle was included in black.

Table 4-23 indicates the resulting known 25 parameters that were obtained for each of the six run. The parameters are compared within the three pairs RC/AC.

The highlighted cells indicate for each pair RC/AC for which case the parameter is of a larger value.

	RC run06	AC run16	run06/ run16	RC run10	AC run20	run10/ run20	RC run14	AC run24	run14/ run24
AccMax	1207.76	829.09	1.46	581.25	640.13	0.91	825.43	5.79	1.42
AccMean	7.64	5.18	1.47	5.06	4.10	1.24	5.38	4.47	1.20
AccRMRatio	4.72	5.17	0.91	4.93	5.56	0.89	4.95	5.19	0.95
AccRMS	36.11	26.85	1.34	25.01	22.81	1.10	26.66	23.25	1.15
DeflectionMax	0.53	0.37	1.44	0.49	0.36	1.33	0.42	0.32	1.28
DeflectionMean	0.09	0.08	1.12	0.09	0.08	1.10	0.08	0.08	0.97
DeflectionRMRatio	1.66	1.40	1.19	1.55	1.36	1.14	1.48	1.30	1.13
DeflectionRMS	0.15	0.11	1.33	0.14	0.11	1.25	0.12	0.11	1.1
SpeedMax	3.69	2.65	1.39	2.41	2.08	1.16	2.54	2.33	1.09
SpeedMean	0.30	0.23	1.33	0.24	0.20	1.22	0.21	0.19	1.12
SpeedRMRatio	1.70	1.75	0.97	1.71	1.73	0.99	1.75	1.76	0.99
SpeedRMS	0.52	0.40	1.30	0.42	0.35	1.21	0.38	0.34	1.11
ErrorMean	0.07	0.06	1.18	0.07	0.06	1.10	0.07	0.06	1.1
ErrorRMRatio	1.65	1.73	0.95	1.66	1.66	1.00	1.67	1.72	0.97
ErrorRMS	0.12	0.11	1.13	0.12	0.11	1.09	0.12	0.11	1.07
PT1_K	1.16	0.91	1.28	1.11	0.94	1.18	0.96	-	-
PT1_TD	0.00	0.00	0.87	0.00	0.00	0.94	0.00	-	-
PT1_TI	0.06	0.08	0.80	0.08	0.11	0.70	0.08	-	-
PT1_Te	0.41	0.44	0.93	0.41	0.47	0.88	0.41	-	-
PT1_QIE	1.95	2.05	0.95	1.74	1.71	1.02	1.66	-	-
PT2_K	1.13	0.87	1.30	1.07	0.87	1.24	0.93	0.86	1.08
PT2_Te	0.47	0.50	0.96	0.49	0.50	0.99	0.49	0.50	0.99
PT2_QIE	2.08	2.16	0.96	1.89	2.06	0.92	1.77	1.96	0.91
CHRating	6	7	0.86	4	6	0.67	3	3	1.00
PSD_Area	6.05	3.46	1.74	5.80	3.61	1.61	4.48	3.48	1.29

Table 4-23: Comparing RC vs. AC

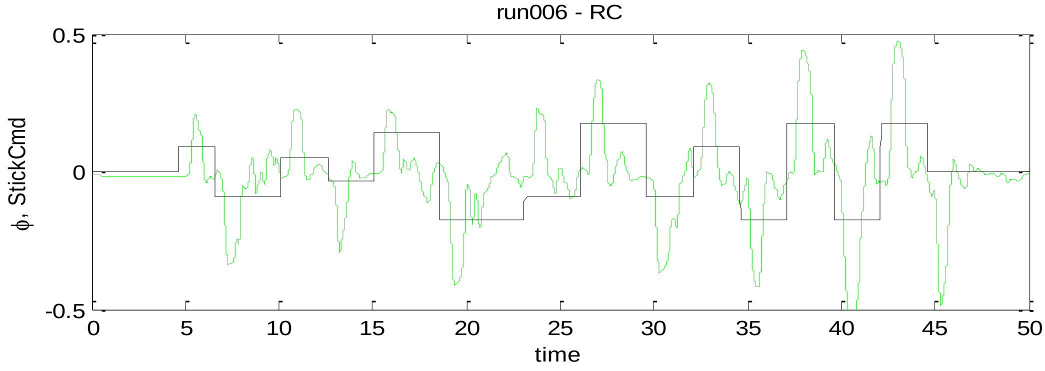


Figure 4-66: StickCmd, target bank angle over time, run006

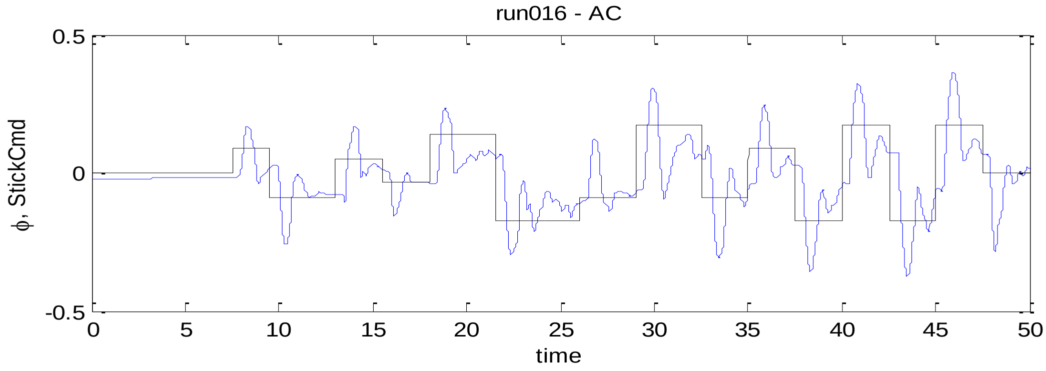


Figure 4-67: StickCmd, target bank angle over time, run016

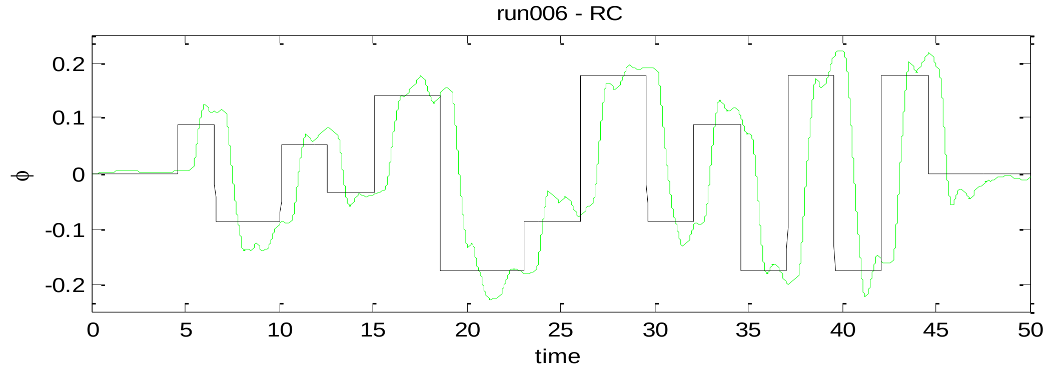


Figure 4-68: Actual bank angle, target bank angle over time, run006

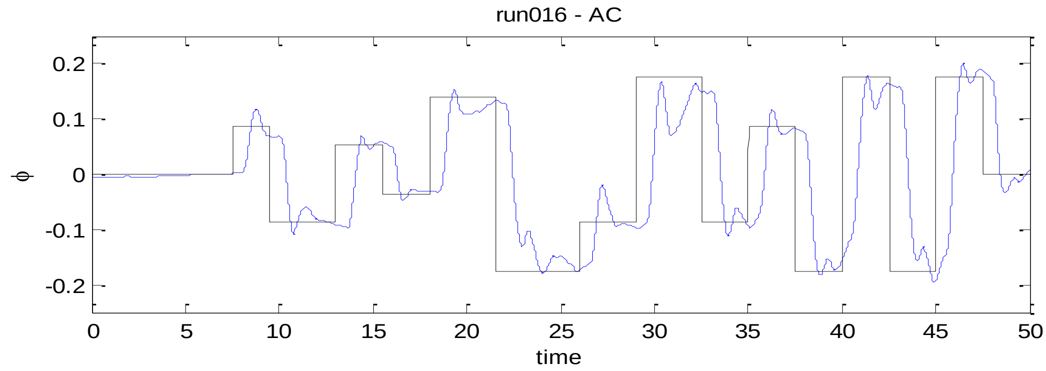


Figure 4-69: Actual bank angle, target bank angle over time, run016

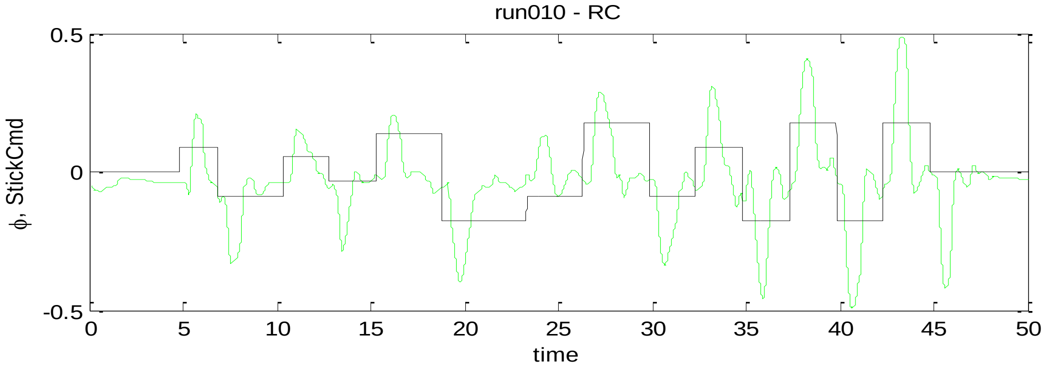


Figure 4-70: StickCmd, target bank angle over time, run010

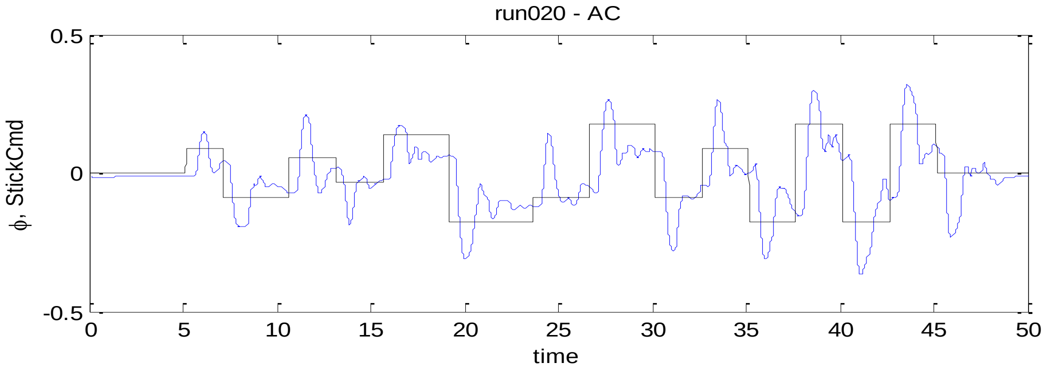


Figure 4-71: StickCmd, target bank angle over time, run020

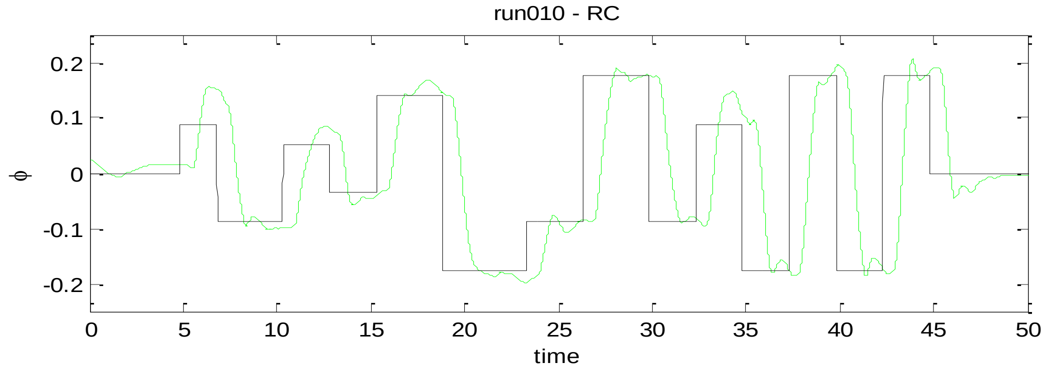


Figure 4-72: Actual bank angle, target bank angle over time, run010

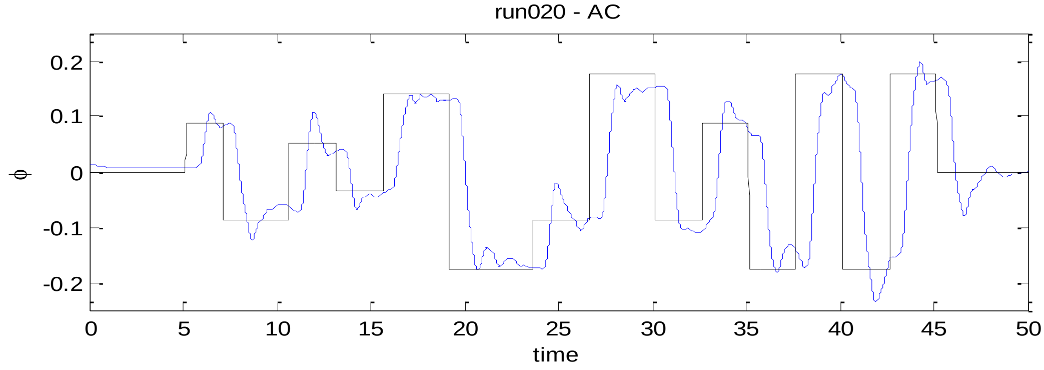


Figure 4-73: Actual bank angle, target bank angle over time, run020

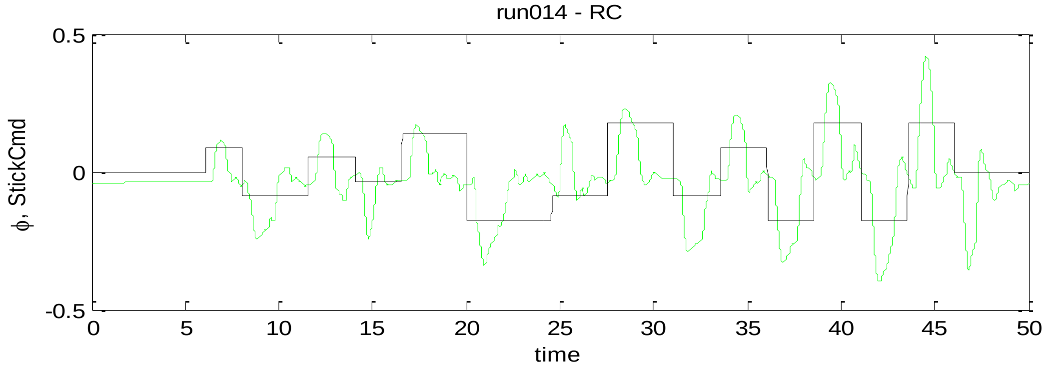


Figure 4-74: StickCmd, target bank angle over time, run014

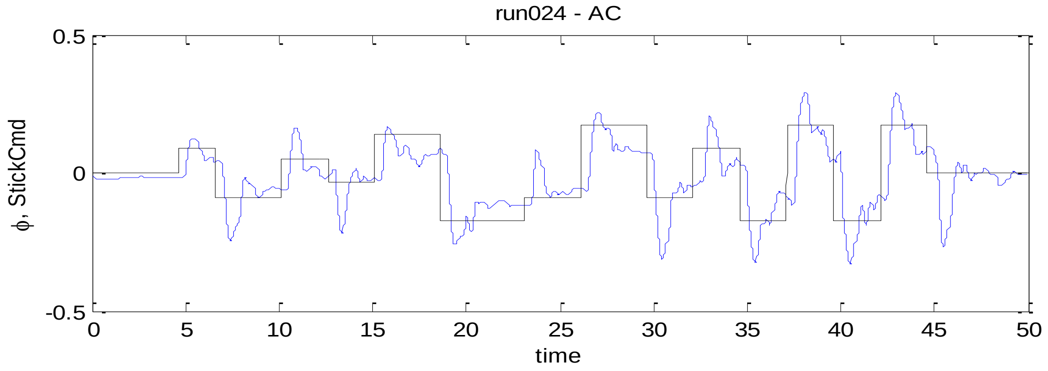


Figure 4-75: StickCmd, target bank angle over time, run024

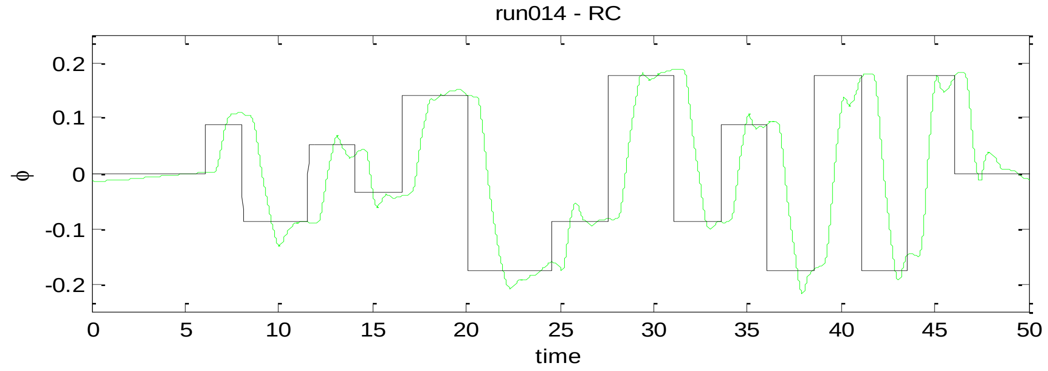


Figure 4-76: Actual bank angle, target bank angle over time, run014

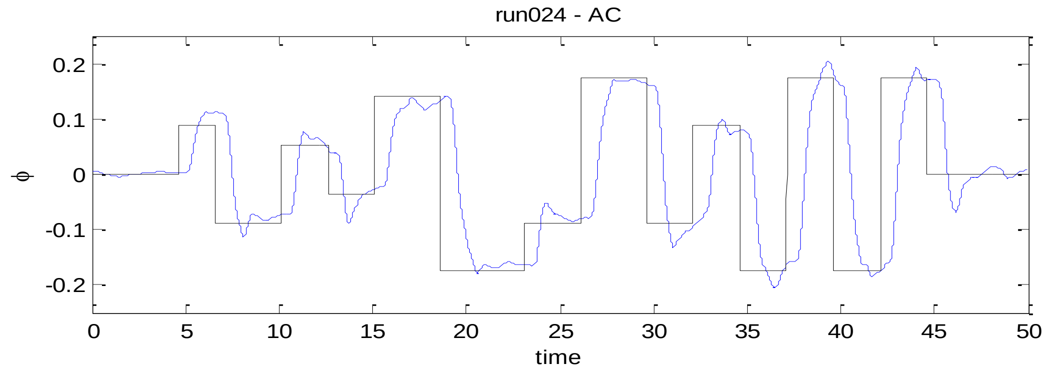


Figure 4-77: Actual bank angle, target bank angle over time, run024

No clear regular differences can be found between RC and AC when comparing the actual bank angle sequences which is a good basis for comparing the differences in pilot's inputs.

Two different tracking strategies are pursued as with the same stick deflection different reactions are caused. While in AC the change of stick position leads to a varying speed, in RC this change provokes a change in acceleration.

As described by Figure 4-65, in order to hold a position in RC the stick deflection must be equal to zero. Especially for run 14 the return to neutral position after an input is clearly identifiable. Moreover, shorter and much larger stick deflections can be observed for RC than for AC.

This can also be seen in Table 4-23: Apart from RMRatio, values for acceleration, speed, deflection and error are larger in RC. Possibly it is easier for the pilot to command higher acceleration and speed by sharp and short inputs than when having to keep a stick in a certain position all the time. It is surprising that also DeflectionMean/RMS are larger in RC than in AC. Obviously, although the stick deflection is more often equal to zero, the peaks make for this average.

4.7 Conclusion

Correlation analysis is an interesting tool to detect relationships between measure data. In cases when there is no mathematic equation between parameters to describe this relationship, tendencies can be discovered.

Unfortunately it is not possible to see via correlation, if there is possibly a third parameter influencing the correlating parameters or if there is a cause-and-effect relationship.

As some correlations show, coincidence cannot always be ruled out. This is why every correlation must be examined critically.

It is remarkable that several correlations were strongly supported by values of RC being larger than values of AC. Unfortunately the amount of measured data being rather small did not allow to examine correlations for only RC or only AC values.

In this particular correlation analysis, 25 possible measures of pilot gain were grouped into eight clusters. By means of the correlation matrix, a clear separation into two groups of clusters can be observed without any connection towards the other group. These two groups are:

1) Stick acceleration and Stick speed
2) Deflection, Error, Pilot Model 1, Pilot Model 2 and PSD

No correlation connecting group 1 and group 2 was found.

It is very surprising that there are clear correlations between Speed and Acceleration but none between Deflection and Speed or Deflection and Acceleration.

As mentioned before, the result of the pilot gain test campaign [Nie11] included the result of rather suitable measures being: Stick acceleration, Speed, Stick deflection and PSD. Correlations between suitable measures were expected here.

In general, the example SpeedRMS vs. PSD_Area shows that the test parameters were too different to allow a reasonable comparison with the pilot gain test campaign. It would still be interesting to also include helicopter pilots in the pilot gain study and figure out what their understanding of high/low gain is.

It can be assumed that (as not being influenced) the helicopter pilot was applying his natural gain. The varying stick settings made him adapt his gain which would lead to the result that there is not the individual pilot gain for every individual that could be measured but a whole range [Nie11] . It would be interesting to see another pilot doing the same runs and figure out if values for the same 25 parameters would be significantly different.

As the ranges of values for the test parameters are not driven by the application of certain pilot gain (low/high gain) the question remains, in which part of his individual gain the pilot was located during the test runs.

5 Conclusion and Outlook

Several aspects of pilot gain are investigated within the present thesis.

At first a literature review including pilot gain and synonyms, that are likely to be used for pilot gain, was performed. The synonyms were differentiated from the term “pilot gain”. Mathematical definitions of pilot gain mostly have a control theory background which is not very tangible and therefore hardly transferable to the human pilot.

Though not being defined as pilot gain, the best definition given was: in order to achieve precise tracking of a reference flight attitude, while one pilot may exert smooth control inputs by moving the stick gently, another pilot might force the stick very hard to accomplish the same specific task [Kae05] .

The question, why one pilot may exert smooth control in inputs while another pilot might force the stick very hard for the same task, still needs investigation. Although there is a lot of literature investigating human control behaviour, it is mostly about general human limits and not concentrating on personality differences.

An established proof of neuronal or physiological parameters reflecting personality is still missing. However, several psychological tests resulting in extraverts being faster and larger in their movements, could be a sign of control behaviour being influenced by personality.

In chapter 4, 25 parameters were compared on the basis of real simulator test data. A correlation analysis was performed to obtain information about dependencies between these possible pilot gain measures. Correlation makes a good methodology to indicate tendencies in statistical data. Several highly significant correlations between measures were obtained which show clear dependencies.

However every result has to be examined carefully. A comparison with results of other simulator tests indicate that pilot gain measures cannot easily be transferred but have to be observed in the respective context.

There is definitely need for further research and a test campaign with preferably a larger group of pilots with a similar background to participate under same test conditions, to learn more about the phenomenon of individual pilot gain.

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