A METHOD FOR INVESTIGATION OF PILOT-VEHICLE SYSTEM DYNAMICS IN WAKE VORTEX ENCOUNTERS

Andrej Schönfeld* and Robert Luckner†
Technische Universität Berlin, Berlin, D-10587, Germany

Alexander V. Efremov‡
Moscow Aviation Institute, Moscow, Russia

Abstract

One of the most hazardous external disturbances for civil and military aircraft is a severe wake vortex encounter. Primary effect on a trailing aircraft is the induced rolling moment. Depending on the encounter conditions also a noticeable reaction around the pitch axis can occur. Investigation of such incidents in flight tests depends on environmental conditions and can be quite expensive. For minimizing these factors and to reduce development time, it is desired to simulate the pilot-vehicle system reaction in ground simulation first. In this paper an approach is presented to model dual-axis pilot behaviour during a wake vortex encounter in manual flight. The Modified Optimal Control Model (MOCM) was chosen to represent the pilot dynamics and for prediction of pilot-vehicle system responses in such surprisingly occuring case. Since the model requires a continuous input signal for parameterization, the assumption was made that manual control is carried out first in turbulent atmosphere. Adapted to the turbulence signal, the aircraft flies into the wake vortex and the pilot starts reacting to the turbulence, not changing his stereotype immediately. Experimentally obtained operator results successfully demonstrate the applicability of this extrapolation for the first half oscillation of the wake vortex signal. Besides linear aircraft dynamics, experiments have been executed for nonlinear actuator dynamics, too.

Nomenclature

$\underline{c}$	Control Vector
$\underline{\dot{c}}$	Control Rate Vector
$\underline{c}_p$	Optimal Control Input
J	Cost Function
K_{ba}	Gain Coefficient of Y_{ba}
L	Roll Moment, Nm
M	Pitch Moment, Nm
$\underline{\underline{Q}}, \underline{\underline{R}}, \underline{\underline{G}}$	Weight Matrices
T	Lag Time, s
t	Time, s
V	Aerodynamic Velocity, m/s
v_y, v_u	Observation and Motoric Noise
$\underline{x}$	State Vector
$\underline{\hat{x}}$	Estimated State Vector
Y_{ba}	Transfer Function from a to b
$\underline{y}_p$	Pilot Observation Vector
α	Angle of Attack
β	Sideslip
δ_a	Aileron Deflection
δ_e	Elevator Deflection
ζ	Damping Coefficient
Θ	Pitch Angle
σ	Standard Deviation
σ^2	Variance
τ	Visual Delay Time, s
Φ	Bank Angle
$\Delta\Psi_{WV}$	Horizontal Encounter Angle
ω	Natural Frequency, rad/s

Subscript

i	Channel number

1 Introduction

1.1 Background

One of the most hazardous external disturbances for civil and military aircraft is a severe wake vortex encounter. Counterrotating vortices as a result of aircraft lift generation create a hazard to followers and are a major contributor to airport capacity limitations.
Primary effect on a trailing aircraft is the induced roll moment, which may lead to a high bank angle for strong disturbances. Several reasons can be stated herefore. First the vortex is a sudden high frequency input signal with sometimes also large amplitudes. Second the pilots do not manage to react in time due to their inherent time delay. Third the aileron effectiveness of real aircraft is limited in bandwidth and magnitude. Encounter intensity is influenced by the size

*Research Scientist, Department of Flight Mechanics, Flight Control and Aeroelasticity.
†Professor, Department of Flight Mechanics, Flight Control and Aeroelasticity.
‡Professor, Department of Flight Dynamics and Control, Head of the Pilot-Vehicle Laboratory.

of the generator aircraft. Depending on the encounter conditions and aircraft dimensions also a coupled reaction in roll, pitch and yaw channel can be observed.
Investigation of such incidents in flight test phase can be expensive and time consuming. To reduce development time and risk during flight test phase ground based investigations are needed first. Mathematical tools can determine safety boundaries of encounter conditions while considering pilot behaviour. These borders can be verified by simulator experiments prior to real test flights.
When the pilot starts to counter the effects of the wake vortex, he becomes part of the closed loop pilot-vehicle system. His behaviour is adaptive in nature and depends on the aircraft dynamics as well as the input signal. In the past several pilot models have been developed to approximate human behaviour for specific tasks.
One investigation done on wake vortex encounter used the Crossover Model [1], which is widely used in the research community. This model describes the pilot behaviour for single-axis tracking task near the crossover frequency. In that study it was tuned by the experimentally obtained side-stick roll command.
Higher computer performance and introduction of optimal control theory led to the development of the Optimal Control Model [2] in the late 1960's, which bears the advantage of calculating the pilot behaviour for a given task. Another advantage is its ability to model coupled multi-axis tasks, too. All investigations with the OCM were undertaken for linear aircraft dynamics, neglecting nonlinearities until now. Disadvantages in the model structure led to the development of a modification presented by /Davidson and Schmidt/ [3] in the early 1990's. Retaining all other fundamental features of the original model, it got the name Modified Optimal Control Model (MOCM).

1.2 Objectives

Main goal of this study was to use the ability of the MOCM algorithm to model multi-axis manual control tasks. It should be applied for investigation of pilot-vehicle system reaction during wake vortex encounter. The encounter situation has been restricted to reactions in roll and pitch channel. Besides linear aircraft dynamics the actuator dynamics were modelled with linear and nonlinear behaviour.
Purpose of the investigation was to develop a method for prediction of wake vortex encounter during manual control flight. For flight safety reasons and for cost reduction such a tool is of great importance in the aircraft design process. Once the feasibility has been demonstrated, the implemented tool could be used to support ground based investigation.

1.3 Method

The developed method uses the MOCM for modelling pilot behaviour during manual control task. For paramterization of this algorithmic model a continuous input signals is required. Thus, to predict the pilot-vehicle system reaction during wake vortex encounter a hypothesis was stated: *Manual control is carried out in turbulent atmosphere prior to the encounter. The pilot flies into the wake vortex adapted to the turbulence input signal. When he reacts to the disturbance, he does not change his behavior instantaneously.*
If this hypothesis is true, then modelling pilot-vehicle system reation in a wake vortex encounter with a pilot model trained to turbulence input is possible. This means human behaviour could be extrapolated from the stabilization task under the premise that the first reactions are the most serious.

2 Pilot Model

Basis of the OCM development process and its derivatives is the assumption that a highly-trained human operator during a high precision task acts as an optimal controller within his psycho-physiological limitations. He does this by estimating the states of a controlled system and developing a control strategy while minimizing a quadratic cost function. This function considers the n-dimensional state vector $\underline{x}(t)$ and the m-dimensional vectors of control $\underline{c}(t)$ and control rate $\underline{\dot{c}}(t)$. They symbolize operator performance, workload and physical limitations.

$$(1) \qquad J = \int_{-\infty}^{\infty} \left(\underline{x}\underline{\underline{Q}}\underline{x}^T + \underline{c}\underline{\underline{R}}\underline{c}^T + \underline{\dot{c}}\underline{\underline{G}}\underline{\dot{c}}^T \right) dt$$

The weight matrices $\underline{\underline{Q}}$ and $\underline{\underline{R}}$ must be positive semidefinite, the weight matrix $\underline{\underline{G}}$ positive definite.
The algorithmical implementation considers the psycho-physiological processes of information detection, decision making and action execution by adaptation blocks for system state estimation and optimal controller determination. These blocks require the solution of two algebraic Ricatti equations. For modelling, the following attributes of pilot behaviour are taken into account: delay of information detection represented by a time delay $e^{-\tau s}$, addditive observation noise $\underline{v}_y(t)$, additive motoric noise $\underline{v}_u(t)$ and inertia of the neuromotor system considered by a first order lag time T_N. The block scheme of the MOCM is shown in FIG. 1. A linear state-space representation is required for the aircraft dynamics. In contrast to the OCM the visual delay block is placed at the ouput of the system, which is equivalent in linear systems. This allows to describe the adaptation blocks with transfer functions, which is more common in control theory.
Many of the pilot model parameters, e.g. signal-to-noise ratio, neuromotor lag time constant and others

have to be set in advance. From a wide number of experiments [2, 3, 4] it has been determined that the observation signal-to-noise ratio is almost constant 0.01. The motor signal-to-noise ratio for single axis tasks equals 0.003, for multi-axis task this value can significiantly increase from 0.01 up to 0.05 [5]. Neuromotor lag time is normally of the order of $T_N = 0.1\ s$ and can differ for different control channels. Observation time delay is between 0.2 s and 0.5 s.
In FIG. 2 the algorithm is shown that is executed to set up the single-axis pilot model. First the aircraft dynamics are augmented by the perception and observation delay block. Then the optimal controller is calculated for the augmented system. This is done in an iterative procedure until the weightings of the matrix $\underline{\underline{G}}$ correspond to the required neuromotor time lag*. Following, the Kalman-Bucy-Filter is calculated for the augmented system with neuromotor lag. This, again an iterative procedure, is stopped when the desired signal-to-noise ratios are achieved. Once all elements have been determined the pilot model transfer function can be calculated. The modelled behaviour has to be compared to the experiments. If no correlation exists, the model parameters can be adjusted until the model function approximates the pilot behaviour.
In multi-channel tasks the pilot divides his attention to the different channels, which must be taken into account during pilot behaviour modelling. This can be reached by modifying the cost function, normalizing every channel i according to its input signal $\sigma^2_{w_i}$ †:

$$J = min \sum_i \frac{\sigma^2_{ye_i} + g_i \sigma^2_{\dot{c}_i}}{\sigma^2_{w_i}}. \quad (2)$$

This cost function becomes minimal for optimal values of the fractional attention, which are obtained by the approach described in /McRuer and Schmidt/ [5].

3 Simulation Model

3.1 Aircraft Dynamics

For simulation of the encounter aircraft a fighter aircraft from the type SU-17 (SU-22) was chosen. To simplify modelling the aircraft was assumed symmetric and the correlated moment of inertia I_{XZ} was neglected.
The angle of attack was assumed to be small during the whole experiments. Thus, longitudinal and lateral motion have been modelled decoupled. The only control surface deflections considered are from the elevator δ_e and from the aileron δ_a. In FIG. 3 the overall pilot-vehicle system under the influence of disturbances is shown.

3.1.1 Longitudinal Dynamics

Both turbulence and wake vortices can be regarded as $\Delta\alpha$ perturbations. Consequently, they are exciting the short period mode predominantly. The resulting transfer function from elevator to pitch angle can be found in /McRuer, Ashkenas and Graham/ [6]:

$$Y_{\Theta\delta_e}(s) = \frac{K_{\Theta\delta_e}(T_{\Theta 1}s + 1)}{s(s^2 + 2\zeta_{sp}\omega_{sp}s + \omega^2_{sp})}. \quad (3)$$

3.1.2 Lateral Dynamics

In lateral motion strong dependency exists between yaw and roll channel. This cannot simply be neglected during turbulence. Nevertheless, the transfer function in /McRuer, Ashkenas and Graham/ [6] has been simplified. Since the aircraft dynamics were measured at discrete frequencies, differences became visible in the frequency plots between the experiment and mathematical modelling. Close relation in the frequencies of the dutch roll and the zeroes led to peaks in the frequency plots. They altered the behaviour of the open-loop system and complicated comparison. Therefore, the poles of the dutch roll were supposed to cancel the zeros in the relationship from aileron to bank angle:

$$Y_{\Phi\delta_a}(s) = \frac{K_{\Phi\delta_a}}{(T_R s + 1)(T_S s + 1)}. \quad (4)$$

3.1.3 Actuator Dynamics

Real actuators are not only inert in their behavior but also nonlinear. The maximum rates and deflections are limited according to their physical limitations. A nonlinear simplification of actuator behavior is shown in FIG. 4.
For setup of the pilot transfer function in nonlinear case an analytical description of actuator behavior is required instead of a block scheme. In /Graham and McRuer/ [7] the method of statistical linearization is explained that allows to approximate a limit block by a gain coefficient K:

$$K(\dot{\delta}_c) = erf\left(\frac{\dot{\delta}_{cmax}}{\sqrt{2}\sigma_{\delta_c}}\right) \quad (5)$$

This gain depends on the limit value $\dot{\delta}_{cmax}$ and the standard deviation σ_{δ_c} of the block input signal $\delta_c(t)$ via the error function erf. The coefficient is calculated in an iterative procedure until a predetermined limit value is not exceeded between two subsequent gains.
During turbulence flight, deflection angles can be assumed close to zero. Hence, only the rate limit has been taken into account for setup of the pilot model. The gain finally influences on the actuator dynamics by increasing the actuator lag time constant ($K < 1$):

*The proof of this statement is shown in [2] and [3]
†The weight coefficient r_i for the control signal $c(t)$is assumed to equal zero.

(6) $$Y_A(s) = \frac{1}{(T/K)s+1}$$

For the linear case the limitations can be neglected and the gain K equals one. Linear as well as nonlinear actuators have been used in this study. The rate limit has been set $\dot{\delta}_{cmax} = 20\ °/s$ and the lag time $T = 0.03\ s$. Position limits of the control surface deflections depend on the control channel (TAB. 1).

3.2 Turbulence Model

Atmospheric turbulence can be modelled by augmenting the equations of motion with disturbance inputs. A typical way of disturbance description is the usage of gust angles α_T or β_T. Their influence on the aircraft states can be described by the disturbance transfer functions /McRuer, Ashkenas and Graham/ [6]:

(7) $$Y_{\Theta\alpha_T}(s) = \frac{K_{\Theta\alpha_T}(T_{\Theta 2}s+1)}{s^2+2\zeta_{sp}\omega_{sp}s+\omega_{sp}^2}$$

and

(8) $$Y_{\Phi\beta_T}(s) = \frac{K_{\Phi\beta_T}s(T_{\Phi 2}s+1)}{(T_Rs+1)(T_Ss+1)(s^2+2\zeta_d\omega_ds+\omega_d^2)}$$

The gust angles themselves can be considered as stochastic processes defined by velocity spectra. The Dryden wind model is used to model atmospheric turbulence with the flight conditions given in TAB 2. It describes the random velocity profile in each axis by shaping filters feeded by white noise.

3.3 Wake Vortex Modelling

Depending on the horizontal encounter angle $\Delta\Psi_{WV}$ and vortex intensity Γ_{WV} a trailing aircraft will experience strong disturbances in pitch and bank motion. The encounter geometry is shown in FIG. 5.
In this investigation a simplified vortex input signal has been used, symbolizing an additional moment. Both aircraft channels have been disturbed by a damped sinusoidal signal. This represents a horizontal encounter, where both vortices are crossed by the trailing aircraft. It was based on time plots from simulator experiments and mainly depends on the encounter angle $\Delta\Psi_{WV}$. Its general form is:

(9) $$\Delta M = A_{max}e^{-|t-t_0|\omega}\sin\left(\omega(t-t_0)\right)$$

Only the vortex amplitude A_{max} and the frequency ω have been varied. Crossing time of the geometric center of the vortices has been determined by the parameter t_0. The frequency ω is the same for both channels and can be calculated from FIG. 5 for a given encounter angle $\Delta\Psi_{WV}$. Generator aircraft span for the vortex experiments was set to $b = 30m$, three times the encounter aircraft span. The amplitudes A_{max} for both axes were selected in relation to the maximum aileron effectiveness of the encounter airplane and the encounter angle. Their ratio has been derived from experiments.
In FIG. 6 an example for such an approximated input signal in the roll channel is shown. Thereby, the moment has been divided by the moment of inertia I_{XX} to obtain the additional angular acceleration $\Delta\dot{p}$ for better interpretation. Since the plot for the pitch channel looks similar, it is not presented here.
It can be seen that for higher encounter angles the maximum additional roll acceleration is decreasing and the signal gets narrower. Also in longitudinal channel the signal gets narrower, but in contrast the maximum amplitude is increasing.
The transfer functions between the pitch and bank attitude respectively and the additional moment are as follows:

(10) $$Y_{\Theta\Delta M}(s) = \frac{K_{\Theta\Delta M}(T_{\Theta 3}s+1)}{s(s^2+2\zeta_{sp}\omega_{sp}s+\omega_{sp}^2)}$$

and

(11) $$Y_{\Phi\Delta L}(s) = \frac{K_{\Phi\Delta L}(s^2+2\zeta_{wv}\omega_{wv}+\omega_{wv}^2)}{(T_Rs+1)(T_Ss+1)(s^2+2\zeta_d\omega_ds+\omega_d^2)}$$

4 Experimental Setup and Execution

4.1 Workstation

4.1.1 General

All experiments have been executed with the workstation of the Pilot-Vehicle Laboratory (PVL) of the Moscow Aviation Institute. This simulator was built to allow preliminary or basic research for ground based or inflight simulations. It was proven in a wide number of experiments of manual control tasks. At the PVL, investigations regarding to handling qualities and pilot-induced oscillations were executed. The setup of the workstation allows to undertake experiments not only in one axis but also in two axes. Thereby control commands are generated by a side-stick with a feel system of high quality that was developed by specifications of a commercial aircraft manufacturer.

4.1.2 Hardware Elements

The workstation consists of a desk, a standard personal computer, a monitor, an A/D-converter card and a chair with an armrest-mounted 2-axis side-stick. The rudder pedals, which are shown also in FIG. 7, were not used in this study. The stick can be deflected in longitudinal and lateral axes. Thereby, deflections are limited to ±16° in longitudinal and ±20° in lateral axis. Further, the side-stick is equipped with adjustable oil dampers in both axes. Conversion to an electrical signal is realized by battery driven potentiometers that are connnected to the A/D-converter card.

4.1.3 Software

The experiment software was developed in *Matlab/Simulink* and requires a Windows PC with *Matlab* (Version 6.5 or higher). It provides a dialog driven interface for communication with the user and a *Simulink* model of the control loop for execution of real time experiments. After each experiment the time signals of the control error and the pilot reaction in both channels have been saved for comparison to the mathematical modelling.
During manual control task the piloting operator saw an artificial horizon (FIG. 8). There the aircraft states are shown in the coordinate representation. Both error signals e_1 and e_2 are displayed independently from each other in one display. For longitudinal motion the small horizontal bar moves up and down. Deviations in the lateral channel are shown by the long line rotating around the center. Hence, the pilot has been forced to divide his attention to both channels. This led to deterioriated tracking performance in dual-channel task.

4.2 Experiment Execution

The manual control experiments have been effectively divided into two levels. At the first level turbulence experiments were executed to set up the pilot model. Next, the vortex encounters were simulated with linear and nonlinear actuator dynamics. An experienced workstation operator and the author executed the experiments. This was regarded sufficient for principal demonstration of the approach. Both operators got the possiblity to train on the turbulence signal before the experiments.
Turbulence flights were executed as series of three experiments, each with a length of 144 s. The obtained results were averaged over a series in the workstation software. So, several plots for each pilot have been obtained.
The vortex encounters were executed with an overall length of 80 s. The turbulence signal was activated for 48 s and replaced by the vortex signal after a short break. To prevent pilot adaptation to the wake vortex signal, the following parameters were randomly chosen before every experiment: encounter angle, factor of the maximum additonal roll moment and the encounter side (TAB. 3).
Intensity of the turbulence signals has been defined in standard deviation of additional pitch angle σ_Θ and roll angle σ_Φ. Both values are given in TAB. 4. They have been changed for the wake vortex encounter. High values were only necessary to train the pilot to the signal. Low signal amplitudes were necessary to see a clear difference between turbulence and vortex reaction.

5 Results

5.1 Turbulence

All experiment plots of an operator have been drawn in the frequency domain. The lowest and the highest values were used to form a corridor for the desired pilot model. Thus, the pilot transfer function can be regarded as an average of all measurements. In FIG. 9 such a plot can be seen. Correlation is very good between pilot model and experiment, except for the low freqency region of the lateral channel. That was supposed to originate from the operator training level. Therefore, generator span was chosen not to interfere with this deviation. Time delay and lag time were the only varied parameters for the model approximation. In TAB. 5 these times are given. The signal-to-noise ratios (observation 0.01, motor 0.003) and the indifference threshold (zero for all error signals) were kept constant.

5.2 Linear Actuator Dynamics

In total 38 experiments have been executed with linear aircraft dynamics together by both operators. Most of the experiments show initially good correlation with the pilot model in bank channel as can be seen from the example in FIG. 10(a). There the bank response of the pilot model coincides with the experiment even for one period. As time continues pilot behavior starts to differ from model prediction. In pitch channel the plots start to differ already after half an oscillation.
In general can be stated that correlation is better for the lateral channel. Compliance has been observed between a half and up to one period independently of the vortex amplitude. In contrast to this, the correlation in longitudinal channel strongly depended on the vortex intensity due to pilot indifference thresholds. There, correlation is less for small input amplitudes.
In FIG. 10(b) the time plot of the pilot-vehicle system is shown. The compliance time of the pilot-vehicle system to the vortex signal varied in the range between 1.5 and 3 s. During this time the pilot behaviour changed only moderately. Further could be observed that the first amplitude was always the most serious one. In nearly all experiments the pilot-vehicle system with a real operator in the loop reacted with a lower roll angle amplitude.

5.3 Nonlinear Actuator Dynamics

With nonlinear actuator dynamics a similar behavior has been observed. Again around 40 experiments have been executed, where the first half oscillation has been very well approximated in lateral and longitudinal motion. Already after half a period pilot behaviour changed, visible by lower second amplitudes in both motion channels (FIG. 11(a)). Despite the fact that also experiments exist with a whole period closely approximated, it can be stated that reaction time decreases in general for nonlinear case.
Reason for shorter compliance time were the rate and position limits. They led immediately to a more inert aircraft. Actuator rates and positions as well as stick postion reached saturation during wake vortex encounter and did not allow to change the direction instantaneously.
Pilot remnant noise was not considered in mathematical simulation. Nevertheless, the model predicted pilot behaviour sufficient for time processes of the turbulence signal. Pilot-vehicle system reaction deteriorated during wake vortex encounter experiments with nonlinear actuator dynamics (FIG. 11(b)). Especially in bank channel has been observed that the first two amplitudes are the most intense and much higher than with linear dynamics. The second amplitude is in general lower with a real operator in the closed-loop system. Consequently, the pilot model reaction can be regarded more conservative.
For lower encounter angles a harmonic oscillation was generated by the model, showing nonadapted model behavior. Although no input was generated, the pilot model continued to deflect the stick from saturation to saturation. A real operator on the other hand damped any oscillation by changing the stereotype. The pilot achieved this by lowering stick deflection to regain control surface effectiveness. In FIG. 12 the model gain coefficient has been decreased by 30% as soon as the model reaches stick limitations. Thus, the oscillatory behaviour has been heavily damped.
Despite of the operators training level and the limited number of experiments undertaken, the mathematical modelling showed good initial compliance with the wake vortex experiments. Even if the operator delay times varied in every experiments, the basic oscillation character did not change and corresponded to model prediction.

6 Conclusion

Severe wake vortices are a potential hazard to every kind of aircraft. Therefore, prediction of their influence on pilot-vehicle system reaction is essential for coping with this problem.
Under the premise that manual control is carried out in turbulent atmosphere prior to the wake vortex encounter a prediction method has been presented here. The Modified Optimal Control Model (MOCM) was used to model pilot behaviour in pitch and roll channel with linear aircraft dynamics. Actuators have been modelled with linear as well as nonlinear dynamics.
Experiments confirmed the assumption of not instantaneously changing pilot behaviour. Good correlation was achieved for both linear and nonlinear actuator dynamics for at least one half oscillation. The reactions in both simulation and experiments showed to be more serious at the beginning of the encounter. As soon as a real operator started to change his behavior, he reacted better than predicted by the model.
Although no real pilot took part in the experiments the results are encouraging further research. Modelling results for nonlinear dynamics showed tendencies for pilot-induced oscillation. Experiments on the other hand did not show such tendency. By changing the model gain coefficient better compliance with the experiments has been achieved. Therefore, further investigations are desired to examine this transient pilot behavior.

Acknowledgments

This work was part of my diploma thesis at the Moscow Aviation Institute under supervision of Prof. A. V. Efremov. I want to thank all people of the PVL who always supported me. Particularly I want to thank Alexander Vassilevitch Ogloblin for his patient and kind support during my studies and my time in Moscow.

References

[1] Gordon Höhne, Michael Fuhrmann, and Robert Luckner. Critical Wake Vortex Encounter Scenarios. *Aerospace Science and Technology*, 8:689–701, 2004.

[2] D. Kleinman, S. Baron, and W. Levison. An Optimal Control Model of Human Response Part I: Theory and Validation. *Automatica*, 6:357–369, 1970.

[3] John B. Davidson and David K. Schmidt. Modified Optimal Control Model for Computer-Aided Design and Analysis. Technical Report NASA TM-4384, NASA Langley Research Center, Hampton / USA, October 1992.

[4] A. V. Efremov, A. V. Ogloblin, A. N. Predtechenskiy, and V. V. Rodchenko. *Pilot as a Dynamic System*. Mashinostroenie, Moscow / Russian Federation, 1992.

[5] Duane McRuer and David K. Schmidt. Minimum Flying Qualities Volume II: Pilot Modeling for Flying Qualities Applications. Technical Report F33615-85-C-3610, Wright Research Develop-

ment Center, Flight Dynamics Laboratory, Wright-Patterson AFB / USA, 1989.

[6] Duane McRuer, Irving Ashkenas, and Dunstan Graham. *Aircraft Dynamics and Automatic Control*. Princeton University Press, Princeton, New Jersey / USA, 1973.

[7] D. Graham and D. T. McRuer. *Analysis of Nonlinear Control Systems*. Wiley, New York / USA, 1961.

[8] Guido Weber. Development of Criteria for Flying Qualities Prediction Using Structural Modelling of Human Pilot Behaviour in the Longitudinal Precise Tracking Task. Technical report, Institut für Luft- und Raumfahrttechnik, Fachbereich Flugmechanik und Flugregelung, Technische Universität Berlin, 15th May 2005.

A Appendix

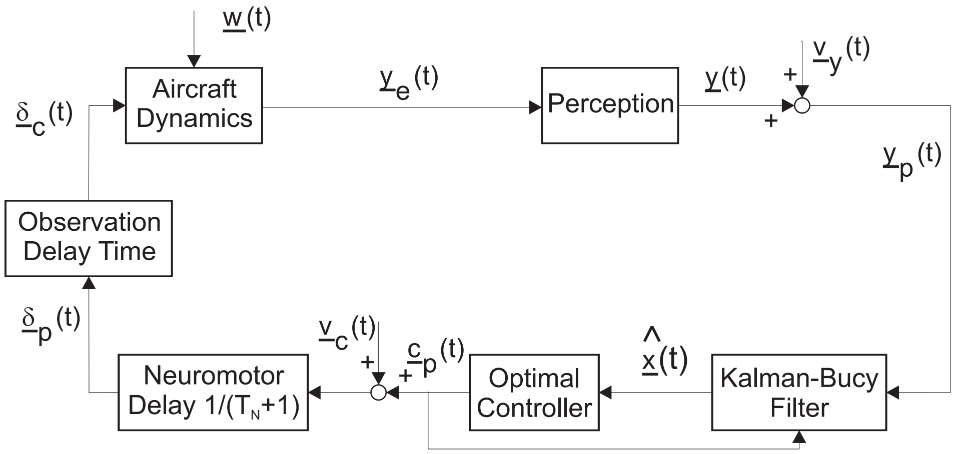


Figure 1: Modified Optimal Control Model

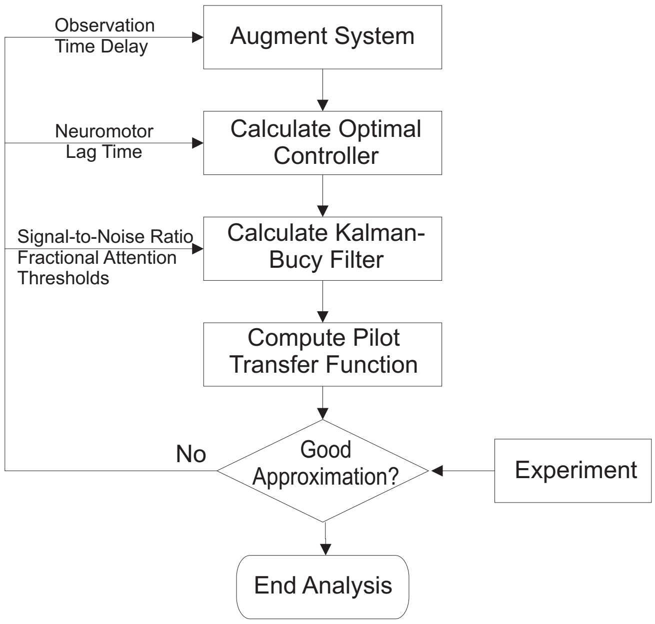


Figure 2: Algorithmic Setup of the Modified Optimal Control Model

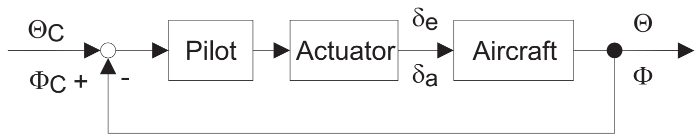


Figure 3: Disturbed Aircraft Dynamics

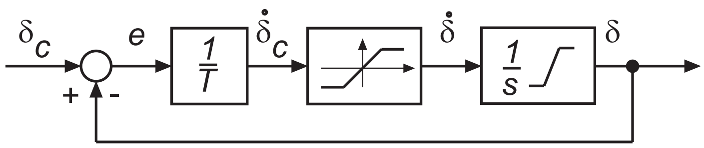


Figure 4: Nonlinear Actuator Dynamics

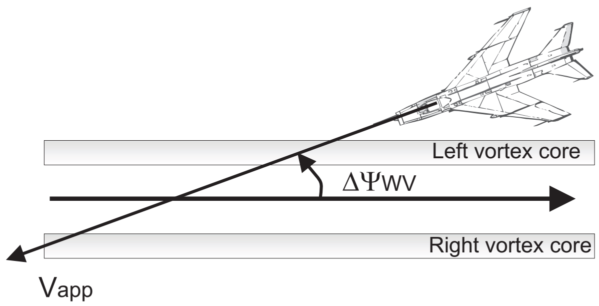


Figure 5: Vortex Encounter Conditions

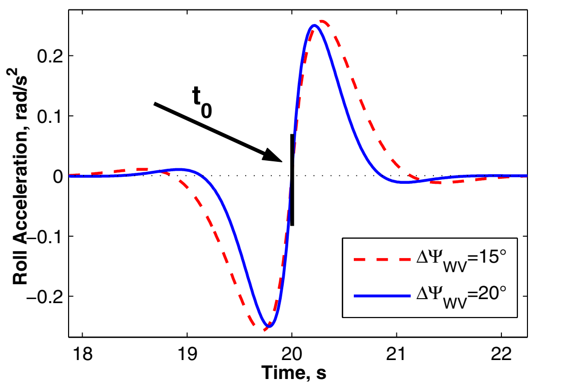


Figure 6: Vortex Approximation in the Roll Channel

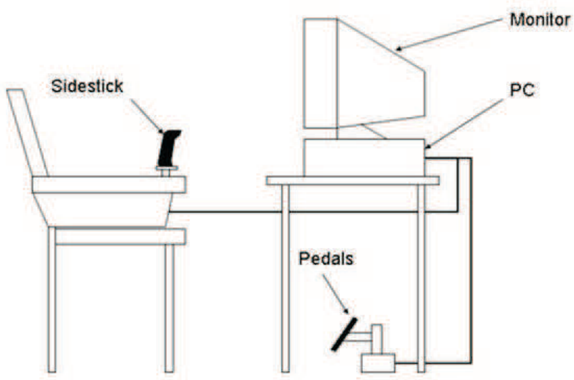


Figure 7: General Workstation Setup [8]

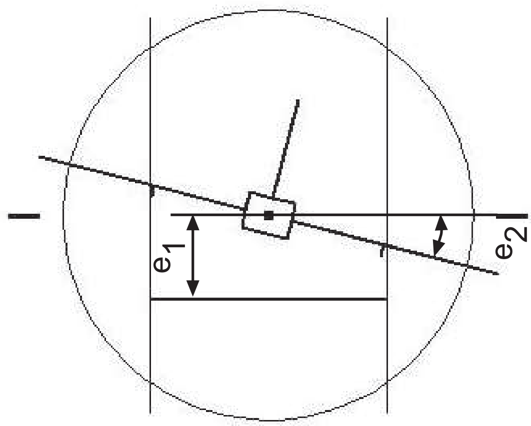
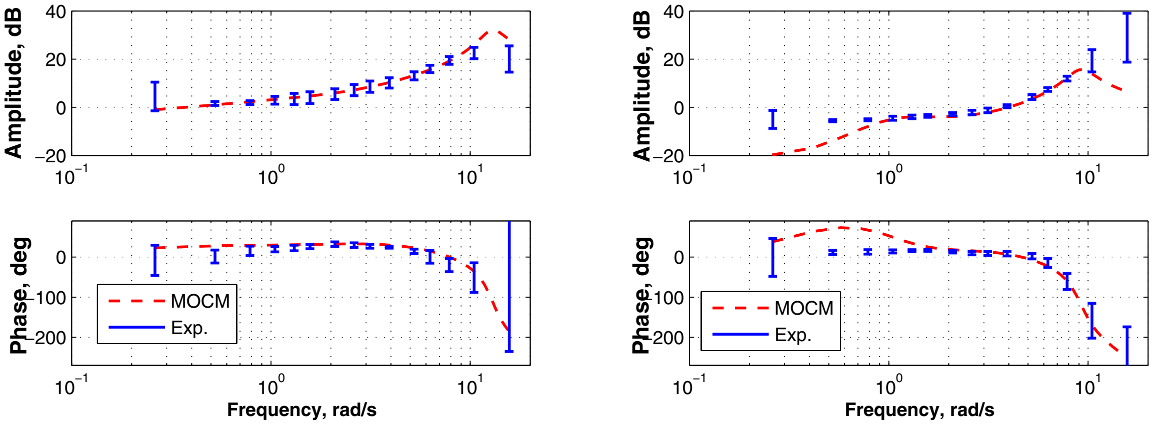
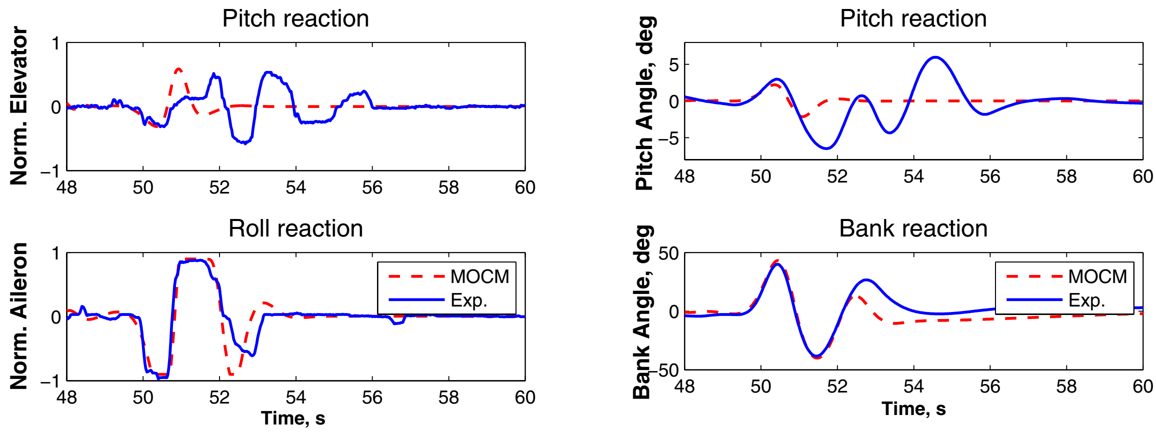


Figure 8: Display for the Experiments



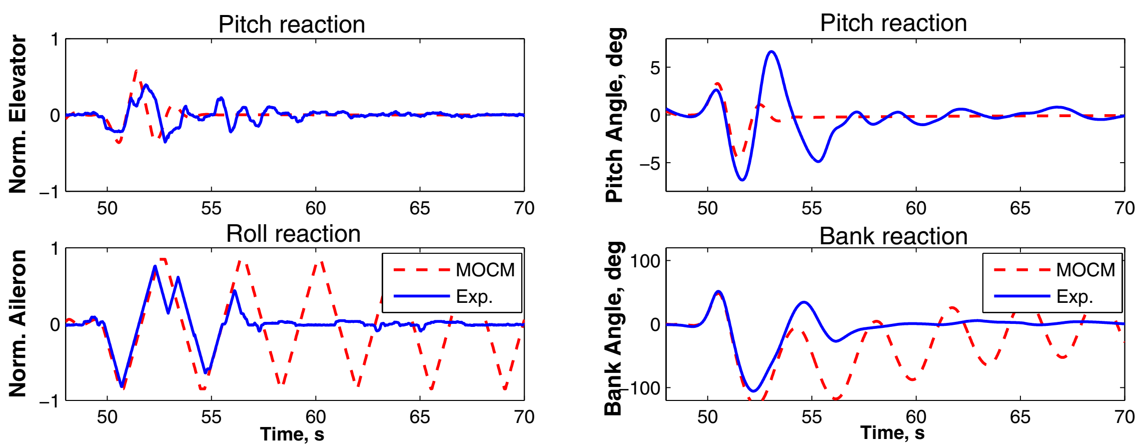
(a) Longitudinal Channel (b) Lateral Channel

Figure 9: Bode plots of measured and modelled pilot behaviour



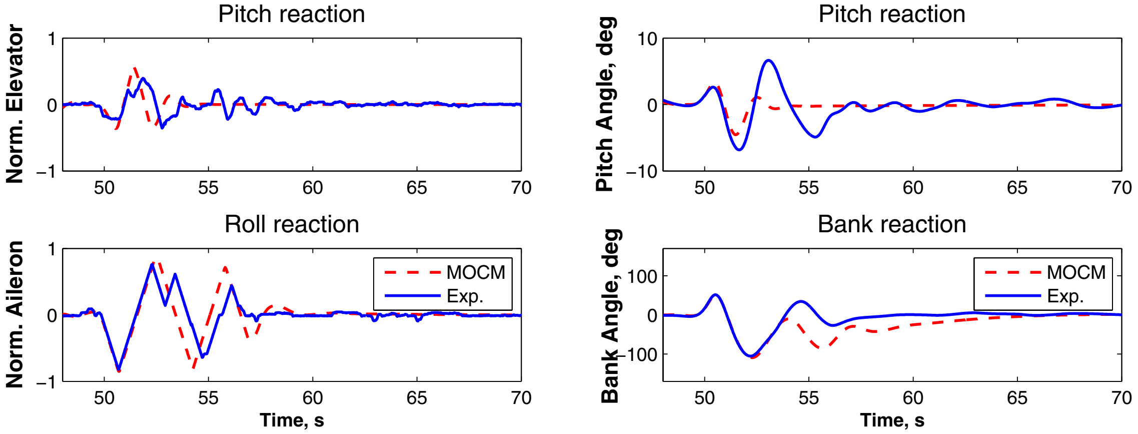
(a) Pilot Reaction (b) Pilot-Vehicle System Reaction

Figure 10: Linear Aircraft dynamics ($\Delta\Psi_{WV} = 15°$, Amplitude Factor 2)



(a) Pilot Reaction (b) Pilot-Vehicle System Reaction

Figure 11: Nonlinear Aircraft dynamics ($\Delta\Psi_{WV} = 15°$, Amplitude Factor 2)



(a) Pilot Reaction

(b) Pilot-Vehicle System Reaction

Figure 12: Nonlinear Aircraft dynamics with gain adjustment ($\Delta\Psi_{WV} = 15°$, Amplitude Factor 2)

Aircraft mass	m	13.500	kg
Wing area	S	34	m^2
Overall length	l	19.03	m
Span	b	10.04	m
Chord	l_μ	4.157	m
Max. elevator deflection	δ_{emax}	$-10°$,$20°$	
Max. aileron deflection	δ_{amax}	$\pm 17°$	

Table 1: Aircraft Parameters (Su-17)

Flight altitude	H	50	m
True Airspeed	V	80	m/s
Angle of Attack	α	5	°
Flight path angle	γ	-2,66	°

Table 2: Reference Flight Conditions

Encounter Angle	5°	-	35°
Encounter Side	-1 (left)		1 (right)
Factor of Maximum Rolling Moment	0.5		2

Table 3: Wake vortex encounter conditions

Channel	Turbulence	Vortex Encounter
Longitudinal, σ_Θ	2°	1°
Lateral, σ_Φ	10°	5°

Table 4: Standard deviation of turbulence

	Longitudinal Motion		Lateral Motion	
	Time Delay [s]	Lag Time [s]	Time Delay [s]	Lag Time [s]
Operator A	0.18	0.06	0.25	0.1
Operator B	0.2	0.05	0.3	0.15

Table 5: Pilot model parameters