

الجامعة
البريطانية في
دبي



The
British University
in Dubai

A Design Study for a Multivariable Feedback Controller for Aircraft Carrier Landing

دراسة في تصميم نظم التحكم ذات المتغيرات المتعددة لنظام الهبوط
على حاملة الطائرات

By

Ziad Abdulla Al-Saadi

Dissertation submitted in partial fulfillment of

MSc Systems Engineering

Faculty of Engineering

Dissertation Supervisor

Professor Robert Whalley

March- 2014

Abstract

This research studies the design of a multivariable control system for aircraft landing. To improve the safety of aircraft landing, handling quality is improved whilst decreasing the number of critical tasks the pilot has to perform simultaneously with improved responsiveness of the aircraft to the pilot's input commands. By adding another control surface on aircraft's horizontal tail the dynamics of the aircraft motion are improved, and the pilot has the minimum number of inputs to effectively control the aircraft. Simulation of the results demonstrate the effectiveness of the dynamic reaction and steady state system response showing the aircraft response to tailplane or aileron input change. Least effort controller design method provides superior results motivating further application studies.

خلاصة البحث

هذا البحث يدرس تصميم نظام التحكم متعدد المتغيرات لحركة الطائرات في مرحلة الهبوط. في خطوة لتحسين سلامة هبوط الطائرات ، و تحسين جودة التحكم من خلال خفض عدد المهام الحرجة التي يقوم بها الطيار في ان واحد وفي نفس الوقت يحسن من استجابة الطائرة لأوامر إدخال الطيار. ان مهمة اضافة سطح تحكم اخر الى الذيل الأفقي على الطائرة ينطوي على تغيير كبير في هيكل الطائرة. في حين أن ديناميكية حركة الطائرة تتحسن ، فان الطيار لا يزال لديه الحد الأدنى من المدخلات للسيطرة على الطائرة بنحو فعال. ان محاكاة النتائج سوف تثبت فعالية ديناميكية الحركة و الاستجابة النهائية مع المتغيرات المختلفة. المحاكاة سوف تعطي أيضا إرشادات لتحديد عمود التحكم التي سيتم استخدامه من قبل الطيار ؛ إما العمود الذي يسيطر على سطح التحكم الموجود على الجناح أو عمود التحكم المتصل مع سطح الذيل الأفقي. في نهاية المطاف ،سهولة تطبيق تقنية الأقل جهد في التصميم و نتائجها المتميزة تحفز إجراء مزيد من الدراسات باستخدام هذه التقنية على مختلف التطبيقات الأخرى.

Acknowledgments

I am indebted to Professor Robert Whalley for his guidance and constant supervision throughout this research. Without his continuous support and priceless advice, this dissertation would not have been possible. Also many thanks to Dr. Ala'a Al Ameer for his constant support, persuasive assistant and encouragement.

Very special thanks to my wife who believes in me. Words cannot express how grateful I am to her. During frustration and giving up time, you provided new perspectives for my life. Your understanding for me being away for hours and days working on this research in parallel with my job is unforgettable. Our children: Adam, Edris, and Ilya have also paid part of the bill for me not spending enough time with them. I thank you from the bottom of my loving heart.

Dedication

To the one who created me from nothing, and bestowed me with countless blessings. To who bestowed me with incredible wife: a wife has been always available helping me to overcome all the hurdles in my life, and patiently standing me at nervous moments. To the one I thank for my sons and daughter: Adam, Edris, and Ilya.

Everything good that is happening to my life is all because of your grace.

My prayer, my living, and my deeds are all for you

Allah!

List of Notations and Abbreviations:

$a_{i,j}(s)$	Elements of $A(s)$, $1 \ll i, j \ll m$
$a_{i,j}, b_{i,j}, \dots, \gamma_{i,j}$	Coefficients of $a_{i,j}(s)$
A	State Space Matrix
$A(s)$	Numerator of $G(s)$
$b(s)$	Polynomial
B	State Space Matrix
b_0, b_1, \dots, b_{m-1}	Coefficients of $b(s)$
C	State Space Matrix
D	State Space Matrix
E	Energy
$e(t)$	Error signal
$d(s), \nabla$	Denominator of $G(s)$
f, f_1, f_2, \dots, f_m	Outer Loop feedback gains
F	Outer feedback loop array
$G(s)$	Transfer Function Array (Input/Output)
h	Feedback path gain
$h(s)$	Feedback path Function
$H(s)$	Feedback path compensator
$H^{-1}(s)$	Inverted Closed Loop Transfer Function matrix

h_{ii}^{-1}	Diagonal terms of inverted closed loop transfer function matrix
I_m	Identity Array
J	Performance Index
k	Forward path gain
$k(s)$	Forward path function
$k \succ h$	Outer Product of k and h
$\langle k, h \rangle$	Inner product of k and h
$K(s)$	Forward path controller model (pre-compensator)
$L(s)$	Left (row) factors
M	Mass (kg)
$n, n_1, n_2, \dots, n_{m-1}$	Gain Ratios
P	Pre-compensator array
Q	Coefficient Array
Q^{-1}	Inversion of open loop transfer function matrix
q_{ii}^{-1}	Diagonal terms in inverted open-loop transfer function matrix
q_{ij}^{-1}	Off diagonal terms in inverted open-loop transfer function matrix
$r(s)$	Transformed reference input
$\bar{r}(s)$	Transformed inner loop reference input
$R(s)$	Right (column) factors
$S(s)$	Sensitivity Array

S_s	Steady State Array
$u(s)$	Transformed input
U	Input Matrix
Y	Output Matrix
$y(s)$	Transformed output
$\Gamma(s)$	Finite time array
$\delta(s)$	Transformed disturbance signal
λ	Eigen Value
INA	Inverse Nyquist Array
L.E.C	Least Effort Control
LQE	Linear Quadratic Estimator
LQG	Linear Quadratic Gaussian
NACA	National Advisory Committee for Aeronautics
PID	Proportional, Integral, and Derivative Controller

List of Figures

Figure 1.1 Control-Response relationships.

Figure 1.2 Location of Aileron, rudder, elevator on the aircraft.

Figure 2.1 F-14 Aircraft actuator surfaces (Balas et. el., 1998).

Figure 2.2 Flap System Geometries (Kroo, I., 2001) .

Figure 2.3 Principal aerodynamic forces on airplane (Kroo, I., 2001).

Figure 2.4 Design of Cayle flying object.

Figure 3.1 Closed loop diagram for multivariable system.

Figure 3.2 Gershgorin Bands.

Figure 4.1 Block diagram of the heave and pitch rate system for changes in elevator deflection.
(Whalley and Ebrahimi, 2000).

Figure 4.2 Open-loop heave and pitch rate following a unit change in input (at wing)

Figure 4.3 F-14 Aircraft dimension Drawings in inches

Figure 4.4 Longitudinal reference geometry.

Figure 4.5 Schematic for aerodynamic forces exerted on the aircraft.

Figure 4.6 Open-loop heave and pitch rate following a unit change in input
(at horizotnal tail).

Figure4.7 A general form for multivariable control system.

Figure 4.8 Block Diagram for the system with pre compensator and controller.

Figure 4.9 Arresting gear configuration in an aircraft carrier (Dorf and Bichop, 2011).

Figure 4.10 simple spring-damper schematic.

Figure 5.1 Root Locus for $(s)/d(s)$.

Figure 5.2 Performance index with relation with gain ratio n .

Figure 5.3 Internal Loop Heave Rate response for a step input.

Figure 5.4 Internal Loop Pitch Rate response for a step input.

Figure 5.5 Closed Loop Heave Rate Response to a step input r_1 at different f values.

Figure 5.6 Closed Loop Pitch Rate Response to a step input r_1 at different f values.

Figure 5.7 Closed Loop Pitch Rate Response to a step input r_2 at different f values.

Figure 5.8 Closed Loop Heave Rate Response to a step input r_2 at different f value.

Figure 5.9 Closed Loop Heave Rate Response following a step disturbance δ_1 at different f values.

Figure 5.10 Closed Loop Pitch Rate Response following a step disturbance δ_1 at different f values.

Figure 5.11 Closed Loop Heave Rate Response following a step disturbance δ_2 at different f values.

Figure 5.12 Closed Loop Pitch Rate Response following a step disturbance δ_2 at different f values.

Figure 5.13 The Dissipated Energy required recovering the aircraft from random disturbance input at different gain ratios.

Figure5.14 Nyquist diagram of q_{11}^{-1} with Gershgorin circles.

Figure5.15 Nyquist diagram of q_{22}^{-1} with Gershgorin circles.

Figure 5.16 Closed Loop Heave Rate Response to a step input r_1 using INA method.

Figure 5.17 Closed Loop Pitch Rate Response to a step input r_1 using INA method.

Figure 5.18 Closed Loop Pitch Rate Response to a step input r_2 using INA method.

Figure 5.19 Closed Loop Heave Rate Response to a step input r_2 using INA method.

Figure 5.20 Closed Loop Heave Rate Response to a step input δ_1 using INA method.

Figure 5.21 Closed Loop Pitch Rate Response to a step input δ_1 using INA method.

Figure 5.22 Closed Loop Heave Rate Response to a step input δ_2 using INA method.

Figure 5.23 Closed Loop Pitch Response to a step input δ_2 using INA method.

Figure 5.24 Energy Dissipation following random disturbances $\delta_1(t)$ and $\delta_2(t)$.

Figure 5.25 The travelled distance on Carrier's Deck surface till complete stop.

Figure 6.1 Closed-loop heave and pitch rate response following a unit step change.(Whalley and Ebrahimi, 2000).

Figure 6.2 Closed-loop dual inputs, dual outputs block diagram for heave and pitch rates.

Figure A.1 Closed loop by least effort controller with $f = 0.8$ Simulation model.

Figure A.2 Closed loop by Inverse Nyquist Array Controller Simulation Model.

Contents

Abstract	I
خلاصة البحث.....	II
Acknowledgements	III
Dedication	IV
List of Notations & Abbreviations	V
List of Figures	13
Contents	XI
Chapter I: Introduction	1
1.1 Research Background	1
1.2 Research Problem Statement	5
1.3 Research Aims and Objectives	6
1.4 Research Dissertation Organization	6
Chapter II: Aircraft Development Review	
2.1 Introduction	8
2.2 Aircrafts Development in the 20th century	10
2.2.1 Aircraft Dynamics	11
2.2.2 Aircraft Control	14
2.2.3 Automatic Feedback Control of Aircraft	20
2.2.4 Stability of Aircraft	21
2.2.5 Handling Quality	25

Chapter III: Aircraft Development Review	27
3.1 Introduction.....	27
3.2 Early History of Control theory Development.....	27
3.3 Development of Classical Control Theory.....	29
3.3.1 PID Controller.....	30
3.3.2 The root locus method.....	30
3.4 Modern control History.....	31
3.4.1 State Space Method.....	32
3.4.2 Optimal Control.....	33
3.5 Robustness.....	37
3.6 Stability.....	38
3.7 Comparison between Classical and Modern control Theory.....	39
3.8 Inverse Nyquist Array (INA)	42
3.8.1 Greshgorin's Theorem.....	44
3.8.2 Achieving diagonal dominance.....	46
3.8.3 Inverse Nyquist Plot.....	46
3.9 Least Effort Methodology.....	47

3.10 Joining of control technology and aircraft dynamic analysis	47
Chapter IV : Research Methodology	50
4.1 Aircraft Mathematical Model	50
4.2 Least Effort Control Method	56
4.2.1 Inner-Loop Analysis	60
4.2.2 Least Effort Optimization	62
4.2.3 Stability of Combined System	64
4.3 Inverse Nyquist Array Method	65
4.4 Aircraft Deck Landing	68
Chapter V: Simulation Results and Discussion	
5.1 Least Effort Controller	70
5.1.1 Least Effort Optimization.....	72
5.1.2 Outer Loop design.....	75
5.2 Disturbance Rejection analysis for L.E.C	81
5.3 Energy Dissipation at different gain ratios	86
5.4 Inverse Nyquist Method	87
5.4.1 Diagonal Dominance.....	87
5.4.2 Output Responses.....	90
5.4.3 Disturbance Rejection for INA method.....	94

5.5 Control Energy Cost Comparison	97
5.6 Landing Distance to Complete Halt	99
Chapter VI: Comparison Study.....	102
6.1 Comparison between single input and dual inputs systems.....	102
6.2 Least Effort versus Inverse Nyquist controllers.....	103
Chapter IV: Conclusion.....	105
References.....	108
Appendix.....	116