SUPERAUGMENTATION AND STABILITY AUGMENTATION CONTROL SYSTEM FOR UNMANNED AERIAL VEHICLE

YASSER ABDULLAH MAHJOUB NOGOUD

A thesis submitted in fulfilment of the
requirements for the award of the degree of
Doctor of Philosophy (Mechanical Engineering)

Faculty of Mechanical Engineering
Universiti Teknologi Malaysia

MAY 2017

Specially dedicated to my family for their love, support and encouragement.

ACKNOWLEDGEMENT

All the praises and thanks to Almighty Allah, the Giver of bountiful blessings and gifts, Whose bounteous blessings enabled me to pursue and perceive higher ideals of life, who bestowed me good health, courage and knowledge to carry out and complete my work. Prayers and peace of Allah be upon the noble Prophet Muhammad (SAWW) who enabled me to recognise my lord and creator.

My PhD life is representing a rich phase with many challenges, and much inspiration to gain experience and knowledge. I would like to express my heartfelt gratitude for all the people who accompanied me to reach this point.

First of all, I would like to express my deepest gratitude to Assoc. Prof. Ir. Dr Suhaimi bin Mansor for his continuous guidance, insightful, constructive criticisms, support, supervision and encouragement for the past four and half years. Dr Suhaimi bin Mansor has been a great source of inspiration for me and has always been open to discussing ideas and answer questions. Under his advice throughout the years, I not only learned how to solve problems but also built a vision to future research directions.

I greatly appreciate Universiti Teknologi Malaysia and Aeronautics Laboratory (Aero Lab) for providing the facilities which enabled this work to be accomplished. I am indebted to the technicians of the Aeronautical Lab, and I would like to thank them. I would like to thank my friends who helped me during my postgraduate life. Special thanks to Kannan Perumal, Chan Wei Chung, Boo Koon Yan, Nur Amalina Musa, Airi Ali and mohd hasrizam Che Man.

Finally, I must mention that it was mainly due to my family’s support during the entire academic career, which enabled me to complete my work. I once again would like to admit that I owe all my achievements to my most loving father Abdullah, Mother Norah, brothers especially Faisal and Abdulrahman, sisters, my lovely wife Hadeel, my daughter Renad and my son Mohammed, who means most to me, for their prayers, love, understanding and support.

ABSTRACT

It is always a challenge to compromise between stability and controllability in the design of an aircraft. The challenge is becoming bigger in designing a flight control system of a small, light weight and low speed unmanned aerial vehicle (UAV). This type of UAV is facing a higher degree of difficulty because of its constraints in stability margin due to the limitation of the centre of gravity locations and experiencing more problems in control system when flying in air turbulence (severe wind gust or crosswind). This research work is focused on analysis, design and simulation of a robust flight control system (FCS) for a small UAV to make it capable of flying in severe gusty conditions. A combination of the variable stability technique along with advanced flying and handling qualities (FHQ) requirements are used to reduce the gust effect on the aircraft. A low-speed UTM-UAV is used as a testbed for this research. A mathematical model for the aircraft including gust velocity components was formulated based on a combination of experimental wind tunnel with theoretical and empirical methods to estimate the aerodynamics coefficient, thus stability and control derivatives. A linearized longitudinal and lateral-directional equations of motion of the aircraft in the state-space form were developed and validated against a non-linear model. Matlab/Simulink simulation algorithm was developed to analyse and evaluate the dynamic behaviour of the UAV at different speeds and CG locations. The simulation results show that the selection of particular stability and control derivatives has a significant influence on the FHQ level of the aircraft gust response for a small UAV. The superaugmentation FCS that consisted of stability augmentation system (SAS) and command stability augmentation system (CSAS) was developed to improve the dynamic characteristics of the longitudinal aircraft. A simulation result shows that the superaugmented aircraft is capable of operating in severe gust environments than augmented aircraft, and puts less strain on the elevator activity in both extreme and calm weather conditions. A comparison of superaugmented aircraft to augmented aircraft shows a significant reduction (70-80%) in undesirable pitch motion caused by a vertical gust in which, that level 1 flight phase Cat.C can be achieved.

.

ABSTRAK

Kompromi antara kestabilan dan kawalan sering menjadi masalah utama dalam proses merekabentuk sesebuah pesawat terbang. Masalah ini menjadi lebih besar dalam proses rekabentuk sistem kawalan penerbangan pesawat tanpa juruterbang (UAV) kategori kecil, ringan dan berkelajuan rendah. Pesawat kategori ini akan menghadapi cabaran yang lebih rumit kerana sering mengalami kekangan jidar kestabilan yang disebabkan oleh kedudukan pusat graviti yang terhad dan menghadapi tambahan masalah kepada sistem kawalan bila diterbangkan dalam keadaan udara yang bergelora (badai udara yang kuat atau angin lintang). Kajian penyelidikan ini tertumpu kepada analisis, rekabentuk dan simulasi sistem kawalan penerbangan (FCS) yang berdaya tahan untuk pesawat UAV kecil yang mampu diterbangkan dalam keadaan badai udara yang kuat. Kombinasi teknik kestabilan pembolehubah bersama keperluan kualiti penerbangan dan kawalan (FHQ) termaju digunakan untuk mengurangkan kesan badai ke atas pesawat. Pesawat UTM-UAV berhalaju rendah telah digunakan sebagai kajian dalam penyelidikan ini. Model matematik untuk pesawat termasuk komponen halaju badai telah diformulasikan berdasarkan kombinasi hasil ujian terowong angin, teori dan kaedah empirikal untuk mendapatkan pekali aerodinamik, seterusnya nilai-nilai terbitan kestabilan dan kawalan pesawat. Persamaan gerakan membujur dan melintang lelurus pesawat dalam bentuk matriks keadaan ruang telah dibangunkan dan disahkan menggunakan pesamaan taklelurus pesawat. Algoritma simulasi telah dibangunkan dalam Matlab/Simulink yang digunakan untuk analisis dan penilaian ciri-ciri dinamik pesawat pada kelajuan berbeza dan pada pusat graviti yang berlainan. Keputusan simulasi menunjukkan pemilihan beberapa terbitan kestabilan akan memberi kesan yang tinggi kepada tahap FHQ terhadap kesan badai untuk pesawat kecil UAV. FCS superimbuhan yang merangkumi sistem kestabilan imbuhan (SAS) dan arahan sistem kestabilan imbuhan (CSAS) telah dibangunkan untuk memperbaiki ciri-ciri dinamik membujur pesawat. Hasil keputusan simulasi menunjukkan pesawat superimbuhan mampu beroperasi dalam keadaan situasi badai yang kencang berbanding pesawat imbuhan dan memberi kesan pengurangan kepada aktiviti penaik dalam keadaan cuaca buruk dan cuaca tenang. Perbandingan antara pesawat superimbuhan dan imbuhan menunjukkan pengurangan besar (70-80%) kepada sambutan yang tidak diingini dalam pergerakan anggulan yang disebabkan oleh badai udara menegak di mana tahap 1 fasa penerbangan Cat.C dapat dicapai.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

6DOF - Six Degrees-of-Freedom

CAP - Control Anticipation Parameter

CG - Center of gravity

CSAS - Command and Stability Augmentation System

DOF - Degrees of freedom

EOM - Equations of Motion

ESDU - Engineering Science data Unit

FAR - Federal Aviation Regulations

FHQ - Flying and Handling Qualities

ISA - International Standard Atmosphere

JAR - Joint Aviation Requirements

LST - Low Speed Tunnel

MIL-STD - Military Standard

MIMO - Multiple-Input Multiple-Output

MRC - Moment Reference Centre

PSD - Power Spectral Density

SAS - Stability Augmentation System

UAV - Unmanned Aerial Vehicle

LIST OF SYMBOLS

A - State matrix

a - Speed of sound

AR - Aspect ration

b - Wing span

C_D - Coefficient of drag

C_{Do} - Zero angle of attack drag coefficient

C_l - Rolling moment coefficient

C_L - Lift coefficient

C_{Lo} - Zero angle of attack lift coefficient

$C_{L\alpha}$ - Lift curve slope

C_m - Pitching moment coefficient

$\bar{C}$ - Mean aerodynamic chord

C_{mo} - Coefficient of moment at zero lift, coefficient of moment at zero angle of attack

$C_{m\alpha}$ - Slope of C_m - α plot

C_n - Yawing moment coefficient

$\mathrm{C_x}$ - Axial force coefficient

$\mathrm{C_y}$ - Side force coefficient

C_{y_r} - Aerodynamic side force damping derivative

C_{y_β} - Aerodynamic side force derivative

C_z - Normal force coefficient

C_τ - Thrust coefficient

D - Null matrix

DB - Dropback

E - Disturbance matrix

e - Oswald's efficiency factor

F	-	Force
g	-	Gravitational acceleration, 9.81m/s
H	-	Angular momentum, Altitude variation
h	-	Height
I_x I_y I_z	-	Moment of inertia about x, y and z axis
I_{xy} I_{yz} I_{xz}	-	Moment of inertia about xy, yz and xz axis.
K	-	Controller gain; Drag factor due to lift
k_i	-	Integral controller gain
k_m	-	Feedforward gain
k_n	-	Static margin
K_q	-	Pitch rate feedback gain
k_α	-	Angle of attack feedback gain
L	-	Lift
L_u, L_v, L_w	-	Turbulence scale lengths in axial, lateral and normal directions
M	-	Pitching moment
m	-	Aircraft mass
N	-	Yawing moment
N_α	-	Normal load factor per unit angle of attack
P	-	Pressure
P_o	-	Pressure at sea level
q_m	-	Pitch rate overshot value to a step elevator input
q_s	-	Pitch rate steady state response to a step elevator input
R	-	Universal gas constant
S	-	Wing reference area
T	-	Time
T_L	-	Temperature laps rate
T_o	-	Temperature at sea level
T_r	-	Roll mode time constant
T_s	-	Spiral mode time constant
T_{θ_2}	-	Second numerator zero in pitch rate and attitude transfer functions

u - Axial velocity perturbation

V - Lateral velocity perturbation

w_g - Vertical gust velocity

X - Axial force component: Axial position

X_{cg} - CG Centre of gravity longitudinal position

X_n - Neutral point longitudinal position

y - Lateral coordinate in axis system

Y - Lateral force component

z - Normal coordinate in axis system

Z - Normal force component

α - Angle of attack

γ - Flight path angle perturbation

Γ - Wing dihedral angle

δ - Control angle

Δ - Characteristic polynomial: transfer function denominator: increment

δ_a - Aileron angle

δ_e - Elevator angle

δ_r - Rudder angle

ε - Throttle level angle: Pitch rate error

ζ - Damping ratio

ζ_d - Dutch roll damping ratio

ζ_p - Phugoid damping ratio

ζ_p ζ_s - Damping ratio, phugoid, damping ratio, short period

ζ_s - Short period damping ratio

θ - Pitch angle perturbation

Λ - Wing sweep angle

ρ - Density

ρ_o - Density at sea level

σ_u, σ_v, σ_w - Turbulence intensities in axial, lateral and normal directions

τ_e - Time equivalent delay

φ - Bank angle

Φ_{ug} , Φ_{vg} , Φ_{wg} - Dryden power spectra of axial, lateral and normal turbulence velocity

Ψ - Yaw angle perturbation

Ω - Spatial frequency of the turbulence

ω_d - Dutch roll undamped natural frequency

ω_n - Natural frequency

$\omega_{n_{sp}}$ - Short period undamped natural frequency

ω_p - Phugoid undamped natural frequency

LIST OF APPENDICES

CHAPTER 1

INTRODUCTION

1.1 Overview

This chapter covers the problem background of gust insensitive UAV, problem statement, objectives and scope of the current research. First, an introduction covering a brief overview of the topic is presented and followed by the problem background and thinking to the solution based on the work's philosophy. At this point, the scope of the study is briefly clarified. With a specific end goal to answer the problem statement, objectives are laid down. Then, the outline of the thesis is presented.

1.2 Problem Background

Unmanned Aerial Vehicles (UAVs) became widely used in civil and military applications due to their versatility and the fact that they represent no risk to their operators. The demand for improvement of performance, stability and efficiency of the UAV is an important and continuous research topic for the future. Much work has been done for improvement of modelling, performance and flight control for the small UAVs to increase their safety and reliability during flight (Gavrilets, 2015; Hallberg et al., 1999; La Civita, Papageorgiou, Messner, & Kanade, 2002; Paw & Balas, 2011). However, the performance of the small UAV in the gusty wind condition is still distant to their large aircraft counterpart.

Small UAV, are more sensitive to turbulences air. This because it has low inertia so that a disruption gust can change its attitude very quickly. Besides that it has low velocity comparing to large aircraft, so turbulences and gusts can change its airspeed flight condition dramatically over a very short period, resulting in unwanted motion. Up to this point, it seems that there is a significant design tradeoff between an aircraft's ability to fly in gusty conditions and its size. A small UAV is desirable for some reasons such as low cost, safe to fly over urban due to the low probability of injury or fatality in case of crash, because of the small amount of kinetic energy that it has but is obviously harder to operate in turbulence. This visible compromise strictly limits the aircraft that can be used for these types of missions.

The attention in aircraft behaviour in turbulence extends back to the earliest days of aviation. Gusty wind was a major hurdle to Wright brothers to complete their first successful flight. With that problem, they recognised the distinction between gust response and stability of their aircraft (Etkin, 1981). Numerous researchers have made case studies and improvement the sensitivity of UAV to the gusty wind (Fitzgerald, 2004; W. J. Pisano, 2009; Poorman, 2014; Stewart, 1976; Thomasson, 1995; Turkoglu, 2012). From the literature review, it can be classified the techniques that were used to suppressing the gust effect from small UAV in two techniques. First one is the passive method which they intended to remove gust effect from the airframe by using the idea of aerodynamic gust insensitivity (Ifju et al., 2002; W. J. Pisano, 2009). Second Methods by responding to gust using robust control system (De Bruin & Jones, 2016; González, Boschetti, Cardenas, & Carrero, 2012). For instance, Thomasson (1995) was interested in a gust-insensitive aircraft to record smooth-looking video from a UAV in calm to moderate conditions and suggested this might be possible by reducing or zeroing several aerodynamic derivatives through aircraft design. Thomasson (1995) just gave a suggestion without any analysis or further details. W. Pisano and Lawrence (2008) adopted one of Thomasson suggestions by developing a UAV model that has the derivatives of the rolling moment due to sideslip angle, C_{l_β} equal to zero. Although W. J. Pisano (2009) succeeds to reduced the unwanted motion caused by gusts, he increased the drag and weight by adding a fin in the bottom of the vertical tail of the UAV. Moreover, W. J. Pisano (2009) was focused on the lateral dynamics of the aircraft only.

Others reported work attempts to design a robust flight control system to reject the gust and turbulences (Cárdenas, Boschetti, & Celi, 2012; De Bruin & Jones, 2016). However, most of small UAV systems make use of low-cost commercial-off-the-shelf flight control system. Most of these flight control system use classical Proportional-integral-derivative (PID) controllers where ad-hoc methods are used to tune the controller gains in flight. This methodology is time-consuming and high-risk (Chao, Cao, & Chen, 2007). Besides that little attention has been spent on the assessment of flying and handling quality standards. Although awareness of UAV design requirements, elaboration of flying and handling qualities is one of the major steps which will enable the designer to go to the flight test phase confidently. Moreover, develop a reliable, robust flight control system, depending on the accuracy of the UAV mathematical modelling. Three standard approaches to flight dynamic model development are analytical, wind-tunnel and flight test technique (Cook, 2013). Each method can be used to complement one another during the different phase of model development. To reduce cost and time to market, most small UAV used only the analytical methods, which considered less accurate method and may lead to developing weak and dangerous flight control system.

As mentioned before Thomasson (1995) suggested it might be possible to develop gust-insensitive aircraft by reducing or zeroing several aerodynamic derivatives through aircraft design. One of his suggestion was zeroing the pitching moment due to the angle of attack, $C_{m\alpha}$ and as knowing reducing the value of $C_{m\alpha}$ may lead to decreasing the stability of the aircraft in the longitudinal motion. To overcome this instability issue, the superaugmented flight control system may be a solution. The term superaugmented flight control system is not new; it was used by other researchers such as (Gibson, 1995; Myers, McRuer, & Johnston, 1984; Rogers, 1989). It appears to have been coined by Myers et al. (1984) to denote a major class with specific characteristics: the aircraft are statically unstable without augmentation.

Keeping the value of $C_{m\alpha}$ small or even positive all the time is not a practical issue, so the technique of variable stability aircraft or varying CG locations seems to be a good idea. This technique is not new, and it was used in various types of aircraft, such as CONCORDE, Airbus A310-300 and A300-600R, to improve the aircraft performance by extending the range capability (Huber, 1988; Zhang, Yang, & Shen, 2009). Although, the method of varying CG locations used for large aircraft and for the purpose of extending the range capability by management fuel transfer among the plurality of fuel tanks during flight and adjust the CG. However, it may help to improve the sensitivity of the UAV to the gust.

1.3 Problem Statement

By understanding the problem background which has been discussed in the previous section, it can be concluded that issues in the field of sensitivity of the small UAV to gust still need more investigation. Besides developing new ideas for improvement the limitations and gaps left by past research work such as designing a gust insensitive configurations and devices. Furthermore, conventional stability augmentation system to comply the classical flying and handling qualities has a limitation and not robust enough to reduce gust sensitivity especially for small UAV under severe gust conditions. By studying the reasons for inadequate response of small UAV to the gust, improvement can be made by applying robust flight control system and advance flying and handling qualities.

This research will use the benefits of the combination of the superaugmented flight control system along with advanced flying and handling qualities requirements to remove the gust effect on the airframe. Moreover, the proposed control should be able to cater the wide range of aircraft stability margin including unstable configurations.

1.4 Research Objectives

The objectives of this study are defined as:

1. To develop and validate an unaugmented mathematical model for UTM-UAV with control and gust inputs.

2. To simulate and evaluate a variable stability of unaugmented and augmented UAV (i.e., a variation of CG locations) flying and handling qualities assessment.

3. To develop a flight control system for augmented and superaugmented aircraft to satisfy an advanced flying and handling qualities and robustness with control and gust inputs.

1.5 Scope of Study

The scope of this research is to study and reduce the effect of gust on UAV longitudinal motion. To achieve this, the wind tunnel static test, UTM-UAV and gust modelling and the robust flight control system is required. The UTM-UAV mathematical modelling will be achieved based on a combination of experimental wind tunnel and theoretical/empirical data. The superaugmented flight control system design will be accomplished through the flying handling qualities to design a Stability Augmentation System (SAS) and Command Stability Augmentation System (CSAS). The experimental test will conduct at Universiti Teknologi Malaysia Low-Speed Tunnel (UTM-LST). MATLAB and Simulink software tools are used to accomplish the design and performance analysis of the proposed systems.

1.6 Significance of the Study

An unmanned aerial vehicle (UAV) is an aircraft without a pilot on board. It is flying either autonomously or remotely controlled by the pilot. UAVs are currently used for some missions, including observation and attack roles. The application for UAV is increasing dramatically due to their unique capabilities. Developing a small UAV that capable of operating in a gusty wind condition will allow to extending the range of potential uses of a small UAV. All of which underlines the importance of establishing an accurate mathematical model of a UAV to be able to develop new innovative ideas successfully. One of the potential outcomes of this research will be the development of a mathematical modelling of a UTM-UAV with control and gust input. This shows precisely which parameters of aircraft design affect the gust sensitivity of the aircraft and how. This differs from most classical aircraft dynamic texts in that gust effects are typically ignored for simplicity within a linearized formulation. It is hoped that the proposed superaugmentation system will overcome the challenges of operating small UAV in severe gusty conditions. The superaugmented aircraft may do so by reducing unwanted aircraft motion due to severe gust, minimise the elevator activity in extream weather, and guarantee that the aircraft will be on the boundary of level 1 flying and handling qualities requirements under all circumstances. In light of the issues mentioned above, results of this research will contribute to what is currently known about gust insensitive UAV. Nonetheless, the significance of this study is not only limited to knowledge enrichment.

1.7 Thesis Organization

This thesis comprises of six chapters. Each of the following paragraphs explains the contents of each chapter.

The introduction, background of the research work, problem statement, objectives, scope of the research and significant of the study are presented in Chapter 1.

In Chapter 2, The literature review related to this work is presented. Flying and handling qualities requirements, most outstanding flying and handling qualities criteria that used by other researchers for evaluation and also as design rules for flight control system design are presented in this chapter. Then the Overview of mathematical modelling for the aircraft and wind gust was introduced. Finally, this chapter also covers the significant findings of previous studies which are most related to this work. A general background and inspiration from current research that is relevant to the development of a gust insensitive aircraft are provided.

In Chapter 3, the research methodology that used to carry out this research work was explained in detail.

In Chapter 4, the results and discussion of mathematical modelling, wind tunnel test and dynamic analysis are provided.

Chapter 5, provide the results and discussion of superaugmentation flight control system and assessment the UAV with the proposed flight control system with different types of the gust.

In Chapter 6, Conclusions, contributions and recommendations for further work is presented.

REFERENCES

Abbott, I. H., & Von Doenhoff, A. E. (1959). *Theory of wing sections, including a summary of airfoil data*: Courier Corporation.

Abdollahi, C. (2010). *Aerodynamic analysis and simulation of a twin-tail tilt-duct unmanned aerial vehicle*. (Masters of Science), University of Maryland.

Al Swailem, S. I. (2004). *Application of robust control in unmanned vehicle flight control system design*. (Ph.D. Thesis), Cranfield University.

Barlow, J., Rae, W., & Pope, A. (1999). *Low-speed wind tunnel testing*, Jhon Wiley & Sons, Canada.

Bihrle, W. (1966). *A handling qualities theory for precise flight path control*, Air Force Flight Dynamics Laboratory, Research and Technology Division, Air Force Systems Command, United States Air Force.

Blower, C. J., Lee, W., & Wickenheiser, A. M. (2012). *The development of a closed-loop flight controller with panel method integration for gust alleviation using biomimetic feathers on aircraft wings*. Paper presented at the International Society for Optics and Photonics, San Diego, California

Bossi, J., & Bryson, A. (1982). *Disturbance estimation for a STOL transport during landing.* Journal of Guidance, Control, and Dynamics, 5(3), 258-262.

Boughari, Y., Botez, R., Ghazi, G., & Theel, F. (2014). *Evolutionary Algorithms for Robust Cessna Citation X Flight Control.* SAE International Journal of Aerospace. doi:10.4271/2014-01-2166

Cao, Y. H., & Yuan, K. G. (2007). *Aircraft flight characteristics in conditions of windshear and icing*. Aeronautical Journal, 111(1115), 41-49.

Cárdenas, E. M., Boschetti, P. J., & Celi, M. R. (2012). *Design of control systems to hold altitude and heading in severe atmospheric disturbances for an unmanned airplane.* Paper presented at the 50th AIAA Aerospace Sciences Meeting including the New Horizons Forum and Aerospace Exposition. , Nashville, Tennessee. .

Chambers, J. R., & Hall, R. M. (2004). *Historical review of uncommanded lateral-directional motions at transonic conditions*. Journal of aircraft, 41(3), 436-447.

Chang, R. C., Ye, C.-E., Lan, C. E., & Guan, W.-L. (2010). *Stability characteristics for transport aircraft response to clear-air turbulence.* Journal of Aerospace Engineering, 23(3), 197-204.

Chao, H., Cao, Y., & Chen, Y. (2007). *Autopilots for small fixed-wing unmanned air vehicles: A survey*. Paper presented at the Mechatronics and Automation, 2007. ICMA 2007. International Conference on.

Collinson, R. (2011). *Fly-by-wire flight control Introduction to Avionics Systems* (pp. 179-253): Springer.

Cook, M. V. (2013). *Flight dynamics principles: a linear systems approach to aircraft stability and control* (3rd ed.). 225 Wyman Street, Waltham, MA 02451, USA The Boulevard, Langford Lane, Kidlington, Oxford, OX5 1GB, UK: Butterworth-Heinemann is an imprint of Elsevier.

Cook, M. V., & de Castro, H. V. (2004). *The longitudinal flying qualities of a blended-wing-body civil transport aircraft.* Aeronautical Journal, 108(1080), 75-84.

Cook, R. G., Palacios, R., & Goulart, P. (2013). *Robust Gust Alleviation and Stabilization of Very Flexible Aircraft*. Aiaa Journal, 51(2), 330-340. doi:Doi 10.2514/1.J051697

Cooper, K. (1996). *Closed-test-section wind tunnel blockage corrections for road vehicles*. SAE SP-1176.

Cornman, L. B., Morse, C. S., & Cunning, G. (1995). *Real-time estimation of atmospheric turbulence severity from in-situ aircraft measurements.* Journal of aircraft, 32(1), 171-177.

Council, N. R. (1983). *Low Altitude Wind Shear and Its Hazard to Aviation*. National Academy Press, 1, 12.

De Bruin, A., & Jones, T. (2016). *Accurate Autonomous Landing of a Fixed-Wing Unmanned Aircraft under Crosswind Conditions.* IFAC-PapersOnLine, 49(17), 170-175. doi:http://dx.doi.org/10.1016/j.ifacol.2016.09.030

Defense, D. O. (1980). *Militiary specification: Flying qualities of piloted airplanes: MIL-F-8785C*. Retrieved from Washington, DC United States:

Dorf, R. C., & Bishop, R. H. (2014). *Modern Control Systems.* Pearson New International Edition: Introduction to Total Quality, Pearson Higher Ed.

Elgayar, I. (2013). *Mathematical modelling, flight control system design and air flow control investigation for low speed UAVs*. City University London.

Etkin, B. (1981). *Turbulent wind and its effect on flight.* Journal of aircraft, 18(5), 327-345.

Etkin, B., & Reid, L. D. (1982). *Dynamics of flight: stability and control* (3rd ed.). New York: John Wiley & sons, Inc.

FAR. (1991). *Part 23 Airworthiness Standards: Normal, Utility, Acrobatic and Commuter Category Airplanes*. Federal Aviation Regulations: USA.

Fitzgerald, P. (2004). *Flight control system design for autonomous UAV carrier landing*. (PhD), Cranfield University, Cranfield.

Frost, W., & Crosby, B. (1978). *Investigations of simulated aircraft flight through thunderstorm outflows* (NASA-CR-3052, M-263). Retrieved from FWG Associates, Inc.; Tullahoma, TN, United States:

Frost, W., Chang, H.-P., McCarthy, J., & Elmore, K. L. (1985). Aircraft performance in a JAWS microburst. Journal of aircraft, 22(7), 561-567.

Galinski, C. R. (2006). Gust resistant fixed wing micro air vehicle. Journal of aircraft, 43(5), 1586-1588.

Galinski, C., & Goraj, Z. (2004). Experimental and numerical results obtained for a scaled RPV and a full size aircraft. Aircraft Engineering and Aerospace Technology, 76(3), 305-313. doi:Doi 10.1108/00022660410536041

Gavrilets, V. (2015). Dynamic model for a miniature aerobatic helicopter Handbook of Unmanned Aerial Vehicles (pp. 279-306): Springer.

Ghazi, G., & Botez, R. M. (2015). Lateral Controller Design for the Cessna Citation X with Handling Qualities and Robustness Requirements. Paper presented at the 62nd Canadian Aeronautical Society Institute CASI Aeronautics Conference and AGM, Montreal, Quebec, Canada.

Gibson, J. C. (1982). Piloted handling qualities design criteria for high order flight control systems. AGARD Criteria for Handling Qualities of Mil. Aircraft 15 p(SEE N 83-10054 01-08).

Gibson, J. C. (1995). The definition, understanding and design of aircraft handling qualities (9056230115). Retrieved from Delft University of Technology:

Gibson, J. C. (1999). Development of a methodology for excellence in handling qualities design for fly by wire aircraft: Delft University Press Delft.

González, P., Boschetti, P., Cardenas, E., & Carrero, M. (2012). Evaluation of the Flying Qualities of a Light Unmanned Airplane via Flight Simulation. doi:10.2514/6.2012-853

Hahn, K.-U. (1989). Effect of wind shear on flight safety. Progress in Aerospace Sciences, 26(3), 225-259.

Hallberg, E., Komlosy, J., Rivers, T., Watson, M., Meeks, D., Lentz, J., . . . Yakimenko, O. (1999). Development and applications of a rapid flight test prototyping system for unmanned air vehicles. Paper presented at the Instrumentation in Aerospace Simulation Facilities, 1999. ICIASF 99. 18th International Congress on.

Hendarko, M. (2002). Development of a handling qualities evaluation toolbox on the basis of Gibson criteria. Paper presented at the 23rd Congress of International Council of the Aeronautical Sciences, ICAS Toronto, Canada.

Hoblit, F. M. (1988). *Gust loads on aircraft: concepts and applications*. Wright-Patterson Air force Base, Ohio: American Institute of Aeronautics and Astronautics, AIAA, Inc.

Hoh, R. H., & Mitchell, D. G. (1996). *Handling-qualities specification-a functional requirement for the flight control system*. Advances in aircraft flight control, 3-33.

Houbolt, J. C., Steiner, R., & Pratt, K. G. (1964). *Dynamic response of airplanes to atmospheric turbulence including flight data on input and response* (Vol. 199): National Aeronautics and Space Administration.

Huber, B. (1988). *Center of Gravity Control on Airbus Aircraft Fuel, Range and Loading Benefits*. Paper presented at the 47th Annual Conference of the Society of Allied Weight Engineers, Inc., Plymouth, Michigan, SAWE paper.

Ifju, P. G., Jenkins, D. A., Ettinger, S., Lian, Y., Shyy, W., & Waszak, M. R. (2002). *Flexible-wing-based micro air vehicles.* AIAA paper, 705(2001-3290), 1-11.

Ifju, P., Stanford, B., Sytsma, M., & Albertani, R. (2006). *Analysis of a flexible wing micro air vehicle.* Paper presented at the 25th AIAA Aerodynamic Measurement Technology and Ground Testing Conference.

JAR. (1978) *Joint Airworthiness Requirements, JAR-25: Large Aeroplanes*. France: Civil Aviation Airworthiness.

Kaufmann, B. (1993). *Application of optimization to aircraft landing in wind shear*. Journal of Aeronautical, 8, 003.

Kussner, H. G. (1932). *Stresses produced in airplane wings by gusts*. (NACA-TM-654). Retrieved from Washington, DC, United States:

La Civita, M., Papageorgiou, G., Messner, W. C., & Kanade, T. (2002). *Design and flight testing of a high-bandwidth H∞ loop shaping controller for a robotic helicopter*. Paper presented at the Proceedings of the AIAA guidance, navigation, and control conference.

Ljung, L. (2001). *System Identification Toolbox: For Use with Matlab: Computation*, Visualization, Programming: User's Guide, Version 5. USA: The Mathworks.

Mark, W. D. (1981). *Characterization, parameter estimation, and aircraft response statistics of atmospheric turbulence*. (NASA-CR-3463, BBN-4319). Retrieved from NASA, Washington, United States:

Maskew, B. (1987). *Program VSAERO theory Document: a computer program for calculating nonlinear aerodynamic characteristics of arbitrary configurations* (NASA-CR-4023, NAS 1.26:4023, AMI-8416). Retrieved from NASA, Washington, United States:

McLean, D. (1990). *Automatic flight control systems* (Vol. 72): Prentice Hall New York.

McRuer, D., Johnston, D., & Myers, T. (1986). *A perspective on superaugmented flight control-Advantages and problems*. Journal of Guidance, Control, and Dynamics, 9(5), 530-540.

Miele, A., Wang, T., & Melvin, W. (1987). *Optimization and acceleration guidance of flight trajectories in a windshear*. Journal of Guidance, Control, and Dynamics, 10(4), 368-377.

Milonidis, D. E. (1987). T*he development of the mathematical model of a remotely piloted vehicle and an investigation on the use of an extended kalman filter for identification of its aerodynamic derivatives*. (M.phil), Cranfield University, Cranfield.

Mitchell, D. G., Hoh, R. H., Aponso, B. L., & Klyde, D. H. (1994). *Proposed Incorporation of Mission-Oriented Flying Qualities into MIL-STD-1797A.* Retrieved from Wright-Patterson Air Force Base:

Mooij, H. A. (2013). *Criteria for Low-Speed Longitudinal Handling Qualities: of Transport Aircraft with Closed-Loop Flight Control Systems*: Springer Science & Business Media.

Moorhouse, D. J., & Woodcock, R. J. (1982). *Background information and user guide for MIL-F-8785C, military specification-flying qualities of piloted airplanes.* Retrieved from Wright-Patterson Air Force Base, Ohio, USA:

Moorhouse, D., & Woodcock, R. (1980). *US Military Specification MIL–F–8785C.* Retrieved from Wright-Patterson Air Force Base, Ohio, USA:

Moulin, B., & Karpel, M. (2007). *Gust loads alleviation using special control surfaces*. Journal of aircraft, 44(1), 17-25.

Mulgund, S. S., & Stengel, R. F. (1995). *Aircraft flight control in wind shear using sequential dynamic inversion.* Journal of Guidance, Control, and Dynamics, 18(5), 1084-1091.

Myers, T. T., McRuer, D. T., & Johnston, D. E. (1984). *Flying qualities and control system characteristics for superaugmented aircraft.* Retrieved from Dryden Flight I~esearch Facility Edwards, California 93523:

Nelson, R. C. (1989). *Flight stability and automatic control:* McGraw-Hill companies Inc

Norton, P. S. (1967). *The determination of the dynamic response of a small swept wing jet fighter to atmospheric turbulence using the power spectrum method of analysis*. Monterey, California. US Naval Postgraduate School.

Panofsky, H. A., & Dutton, J. (1984). *Atmospheric Turbulence: Models and Methods for Engineering Applications*, 397 pp: John Wiley, New York.

Paw, Y. C., & Balas, G. J. (2011). *Development and application of an integrated framework for small UAV flight control development.* Mechatronics, 21(5), 789-802.

Pisano, W. J. (2009). *The development of an autonomous gust insensitive unmanned aerial vehicle*. (PhD), University of Colorado at Boulder, ProQuest Dissertations And Theses. (AAI3354625)

Pisano, W., & Lawrence, D. (2008). *Autonomous gust insensitive aircraft.* Paper presented at the AIAA guidance, navigation, and control conference, Honolulu.

Poorman, D. P. (2014). *State estimation for autopilot control of small unmanned aerial vehicles in windy conditions*. (Master of Science (MS)), University of Colorado Boulder.

Press, H., Meadows, M. T., & Hadlock, I. (1955). *Estimates of probability distribution of root-mean-square gust velocity of atmospheric turbulence from operational gust-load data by random-process theory*. (NACA-TN-3362). Retrieved from Langley Field, VA, United States:

Rahman, N. u. (2009). *Propulsion and flight controls integration for the blended wing body aircraft*. (PhD), Cranfield University, Cranfield.

Rauf, A., Zafar, M. A., Ashraf, Z., & Akhtar, H. (2011). *Aerodynamic modeling and state-space model extraction of a UAV using DATCOM and Simulink*. Paper presented at the Computer Research and Development (ICCRD), 2011 3rd International Conference on.

Rice, S. O. (1944). *Mathematical analysis of random noise*. Bell System Technical Journal, 23(3), 282-332.

Rogers, W. L. (1989). *Applications of Modern Control Theory Synthesis to A Super-Augmented Aircraft*. (Master's Thesis), DTIC Document. (ADA215431)

Romanelli, G., Castellani, M., Mantegazza, P., & Ricci, S. (2012). *Coupled CSD/CFD non-linear aeroelastic trim of free-flying flexible aircraft.* Paper presented at the 53rd AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics and Materials Conference 20th AIAA/ASME/AHS Adaptive Structures Conference 14th AIAA.

Roskam, J. (1995). *Airplane flight dynamics and automatic flight controls.* (Vol. Part 1). Lawrence, KS 66044, USA: DARcorporation.

Santo Costa, D. E., & Kienitz, K. H. (2009). *A systematic approach to flight control law validation in early design stages*. Paper presented at the 20th International Congress of Mechanical Engineering Gramado, RS, Brazil

Shao, K., Wu, Z., Yang, C., Chen, L., & Lv, B. (2010). *Design of an Adaptive Gust Response Alleviation Control System: Simulations and Experiments*. Journal of aircraft, 47(3), 1022-1029. doi:10.2514/1.46689

Shelton, A., Tomar, A., Prasad, J., Smith, M., & Komerath, N. (2006). *Active multiple winglets for improved unmanned-aerial-vehicle performance*. Journal of aircraft, 43(1), 110-116.

Siegwart, R., Mattio, A., Bouabdallah, S., & Gros, S. (2006). *Modelling and Control of the UAV Sky-Sailor*. (Master Master Project report), Ecole Polytechnique Fédérale de Lausanne, Switzerland.

Snyder, C. T. (1968). *Analog study of the longitudinal response of a swept-wing transport airplane to wind shear and sustained gusts during landing approach* (NASA-TN-D-4477). Retrieved from Washington, United States.

Sprater, A. (1914). *Stabilizing device for flying-machines*: Google Patents.

Stan, D. (1999). *Design and Airworthiness Requirement for Service Aircraft: STAN 00-970*. Retrieved from London, UK Ministry of Defence.

Steinberg, M. (2005). *Historical overview of research in reconfigurable flight control. Proceedings of the Institution of Mechanical Engineers*, Part G: Journal of Aerospace Engineering, 219(4), 263-275.

Stewart, E. C. (1976). *An analytical study and wind tunnel tests of an aeromechanical gust-alleviation system for a light airplane* (NASA-TN-D-8234, L-10635). Retrieved from Hampton, VA, United States.

Stollery, J., & Dyer, D. (1989). *Wing-section effects on the flight performance of a remotely pilotedvehicle*. Journal of aircraft, 26(10), 932-938.

Stull, R. (2000). *Meteorology for scientists and engineers* (2nd ed.). CA, USA: Pacific Grove.

Taylor, G. I. (1935). *Statistical theory of turbulence*. Paper presented at the Proceedings of the Royal Society of London A: Mathematical, Physical and Engineering Sciences.

Thomasson, P. (1995). *The flight dynamics of a gust insensitive unmanned aircraft.* Paper presented at the Control and Guidance of Remotely Operated Vehicles, IEE Colloquium on.

Trebble, W. J. G. (1985). *Low-Speed Wind tunnel Tests on a Full-Scale Unmanned Aircraft (X-RAE1)*. Retrieved from Royal Aerospace Establishment, RAE tunnel

Triputra, F. R., Trilaksono, B. R., Sasongko, R. A., & Dahsyat, M. (2012). *Longitudinal dynamic system modeling of a fixed-wing UAV towards* *autonomous flight control system development: A case study of BPPT wulung UAV platform.* Paper presented at the System Engineering and Technology (ICSET), 2012 International Conference on.

Turkoglu, K. (2012). *Real-time strategies for enhancing aircraft performance in Wind.* (PhD Dissertation), University of Minnesota. Retrieved from http://hdl.handle.net/11299/139705.

Williams, J. E., & Vukelich, S. R. (1979). The USAF stability and control digital DATCOM. Volume I. Users manual. Retrieved from

Williams, J. K., & Meymaris, G. (2016). Remote Turbulence Detection Using Ground-Based Doppler Weather Radar Aviation Turbulence (pp. 149-177): Springer.

Williamson, G., Lewellen, W., & Teske, M. E. (1977). Model predictions of wind and turbulence profiles associated with an ensemble of aircraft accidents.

Wilson, E. B. (1916). Theory of an Aeroplane Encountering Gusts. Proceedings of the National Academy of Sciences, 2(5), 294-297.

Wright, J. R., & Cooper, J. E. (2008). *Introduction to aircraft aeroelasticity and loads* (Vol. 20): John Wiley & Sons.

Yang, M.-H., Ho, C.-S., Lan, C. E., & Hsiao, F.-B. (2010). *Longitudinal handling quality analysis of a civil transport aircraft encountering turbulence*. Journal of aircraft, 47(1), 32-40.

Zhang, J., Yang, L., & Shen, G. (2009). *Modeling and attitude control of aircraft with center of gravity variations*. Paper presented at the 2009 IEEE Aerospace conference.

Zhiping, L., & Fang, T. (2013). *Model derivation and control system simulation for unmanned aerial vehicle*. Paper presented at the 2013 25th Chinese Control and Decision Conference (CCDC).