

SUPERAUGMENTATION AND STABILITY AUGMENTATION CONTROL
SYSTEM FOR UNMANNED AERIAL VEHICLE

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

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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 lurus pesawat dalam bentuk matriks keadaan ruang telah dibangunkan dan disahkan menggunakan persamaan 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 superimbunan yang merangkumi sistem kestabilan imbunan (SAS) dan arahan sistem kestabilan imbunan (CSAS) telah dibangunkan untuk memperbaiki ciri-ciri dinamik membujur pesawat. Hasil keputusan simulasi menunjukkan pesawat superimbunan mampu beroperasi dalam keadaan situasi badai yang kencang berbanding pesawat imbunan dan memberi kesan pengurangan kepada aktiviti penaik dalam keadaan cuaca buruk dan cuaca tenang. Perbandingan antara pesawat superimbunan dan imbunan 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.

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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 ratio |
| b | - | Wing span |
| C_D | - | Coefficient of drag |
| C_{D_0} | - | Zero angle of attack drag coefficient |
| C_l | - | Rolling moment coefficient |
| C_L | - | Lift coefficient |
| C_{L_0} | - | Zero angle of attack lift coefficient |
| $C_{L\alpha}$ | - | Lift curve slope |
| C_m | - | Pitching moment coefficient |
| \bar{c} | - | Mean aerodynamic chord |
| C_{m_0} | - | Coefficient of moment at zero lift, coefficient of moment at zero angle of attack |
| $C_{m\alpha}$ | - | Slope of $C_m - \alpha$ plot |
| C_n | - | Yawing moment coefficient |
| C_x | - | Axial force coefficient |
| C_y | - | Side force coefficient |
| C_{y_r} | - | Aerodynamic side force damping derivative |
| $C_{y\beta}$ | - | 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 overshoot 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 lapse 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 |
| $\zeta_p \zeta_s$ | - | Damping ratio, phugoid, damping ratio, short period |
| ζ_s | - | Short period damping ratio |
| θ | - | Pitch angle perturbation |
| Λ | - | Wing sweep angle |
| ρ | - | Density |
| ρ_0 | - | Density at sea level |
| $\sigma_u, \sigma_v, \sigma_w$ | - | Turbulence intensities in axial, lateral and normal directions |
| τ_e | - | Time equivalent delay |

| | | |
|-----------------------------------|---|---|
| φ | - | Bank angle |
| $\Phi_{ug}, \Phi_{vg}, \Phi_{wg}$ | - | 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 |
| ω_{nsp} | - | Short period undamped natural frequency |
| ω_p | - | Phugoid undamped natural frequency |

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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 supraaugmentation system will overcome the challenges of operating small UAV in severe gusty conditions. The supraaugmented 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.

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