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UAV Smart Wing Control System - proactive control of short-period oscillations

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Declaration

I, Bhagyesh Govilkar declare that this thesis and the work presented in it are my own and has been generated by me as the result of my own original research. I confirm that:

1. This work was done wholly or mainly while in candidature for a degree at this University;
2. Where any part of this thesis has previously been submitted for any other qualification at this University or any other institution, this has been clearly stated;
3. Where I have consulted the published work of others, this is always clearly attributed;
4. Where I have quoted from the work of others, the source is always given. With the exception of such quotations, this thesis is entirely my own work;
5. I have acknowledged all main sources of help;
6. Where the thesis is based on work done by myself jointly with others, I have made clear exactly what was done by others and what I have contributed myself;
7. None of this work has been published before submission.

Introduction

Unmanned Aerial Vehicles are becoming increasingly mainstream. With faster and more efficient ways of manufacturing such as 3D printing gaining momentum, this will only serve to bolster the emerging market. The University of Southampton's SULSA project (Southampton University Laser Sintered Aircraft) produced an UAV that was made entirely from 3D printed parts.

There are several contemporary and potential applications of UAVs: they are widely used in agriculture to give farmers a detailed picture of the health of their farm, the amount of resources such as pesticides required and they can help cut down on labour costs; they are already being used in the defence sector mostly to carry out surveillance and reconnaissance activities, a handful are being used for offensive operations such as the MQ-9 Reaper.

With this increasing usage of UAVs, there is a strong need for a control system that can give the user a stable, reliable and robust aircraft. The aim is to reduce the frequency of UAVs crashing, increase the life-span and reduce the maintenance costs.

In this project, I will be looking specifically at a phenomenon known as a "short-period oscillation". This is one of the two longitudinal dynamic modes that occur on every aircraft, the other being a "phugoid oscillation". Short-period oscillations are characterised by the rapid decay and high frequency. A typical SPO can settle within a second and occurs at 1-2Hz. A pilot can induce a SPO by a sharp pitch input. They can also naturally occur due to a gust (impulsive increase/decrease in airspeed and/or angle of attack).

A UAV control system that does not have a SPO model is vulnerable to growing instability. It can act to reinforce the oscillation instead of canceling them. Thus it is important to systematically analyse and design a model that can handle a SPO.

Acknowledgements

I would like to acknowledge my supervisor, Dr T. Glyn Thomas who provided me with guidance every step of the way and supported my ideas that enabled me to complete this project.. . .

List of Abbreviations

LAH	**L**ist **A**bbreviations **H**ere
WSF	**W**hat (it) **S**tands **F**or

Physical Constants

Speed of Light	$c_0 = 2.997\,924\,58 \times 10^{8}\,\mathrm{m\,s^{-1}}$ (exact)

List of Symbols

a	distance	m
P	power	W ($\mathrm{J\,s^{-1}}$)
ω	angular frequency	rad

Contents

Chapter 1

Current state-of-the-art

The knowledge we currently have and the applications of this knowledge need to be established first to identify the areas in which we lack an understanding and where improvements and optimisations can be made. In this chapter, I intend to do exactly that. By the end of this chapter, it will be clear that there has been little development in this area.

1.1 Flight dynamics

We need to understand flight dynamics to determine the modes of longitudinal oscillations.

I will use the longitudinal equations of motion as a starting point :

$$\begin{bmatrix} \Delta\dot{u} \\ \dot{w} \\ \dot{q} \\ \Delta\dot{\theta} \end{bmatrix} =$$

$$\begin{bmatrix} \frac{\mathring{X}_u}{m} & \frac{\mathring{X}_w}{m} & 0 & -gcos\theta_0 \\ \frac{\mathring{Z}_u}{m-\mathring{Z}_{\dot{w}}} & \frac{\mathring{Z}_w}{m-\mathring{Z}_{\dot{w}}} & \frac{\mathring{Z}_q+mU_\infty}{m-\mathring{Z}_{\dot{w}}} & \frac{-mgsin\theta_0}{m-\mathring{Z}_{\dot{w}}} \\ \frac{1}{I_y}\left[\mathring{M}_u + \frac{\mathring{M}_{\dot{w}}\mathring{Z}_u}{m-\mathring{Z}_{\dot{w}}}\right] & \frac{1}{I_y}\left[\mathring{M}_w + \frac{\mathring{M}_{\dot{w}}\mathring{Z}_u}{m-\mathring{Z}_{\dot{w}}}\right] & \frac{1}{I_y}\left[\mathring{M}_q + \frac{\mathring{M}_{\dot{w}}(\mathring{Z}_q+mU_\infty)}{m-\mathring{Z}_{\dot{w}}}\right] & -\frac{M_{\dot{w}}mg\sin(\theta_0)}{I_y(m-Z_{\dot{w}})} \\ 0 & 0 & 1 & 0 \end{bmatrix} \begin{bmatrix} \Delta u \\ w \\ q \\ \Delta\theta \end{bmatrix} +$$

$$\begin{bmatrix} \frac{\Delta\mathring{X}_c}{m} \\ \frac{\Delta\mathring{Z}_c}{m-\mathring{Z}\dot{w}} \\ \frac{\Delta\mathring{M}_c}{I_y} + \frac{\mathring{M}_{\dot{w}}}{I_y}\frac{\Delta\mathring{Z}_c}{m-\mathring{Z}\dot{w}} \\ 0 \end{bmatrix}$$

The derivation of these equations are fairly straightforward but quite lengthy and can be found in virtually any flight mechanics/dynamics textbook [2].

These equations can be rewritten in the form:

$$\dot{\mathbf{x}} = \mathbf{A}\mathbf{x}+\mathbf{B}$$

Where x is the state vector, **A** is the system matrix (constant) and B is a vector of control forces and moments which can be considered 0.

$$\dot{\mathbf{x}} = \mathbf{A}\mathbf{x}$$

This is a first order ODE which means that the solutions are in the form of

$$\mathbf{x} = \mathbf{x}_0 e^{\lambda t}$$

$$\lambda \mathbf{x}_0 = \mathbf{A}\mathbf{x}_0$$

$$(\mathbf{A} - \lambda \mathbf{I})\mathbf{x}_0 = 0$$

Non-trivial solutions occur when $det(\mathbf{A} - \lambda \mathbf{I}) = 0$. Solving this equation for any given aircraft will give a quartic equation (4th order polynomial) which when solved will give two pairs of complex conjugates. One of the pairs corresponds to the phugoid mode while the other one corresponds to the SPO.

For example, we can consider the Navion aircraft [1]:

$$\mathbf{A} = \begin{bmatrix} -0.09148 & 0.04242 & 0 & -32.17 \\ 10.51 & -3.066 & 152 & 0 \\ 0.2054 & -0.05581 & -2.114 & 0 \\ 0 & 0 & 1 & 0 \end{bmatrix}$$

Computing the eigenvalue of this matrix: The matrix produces two pairs of complex con-

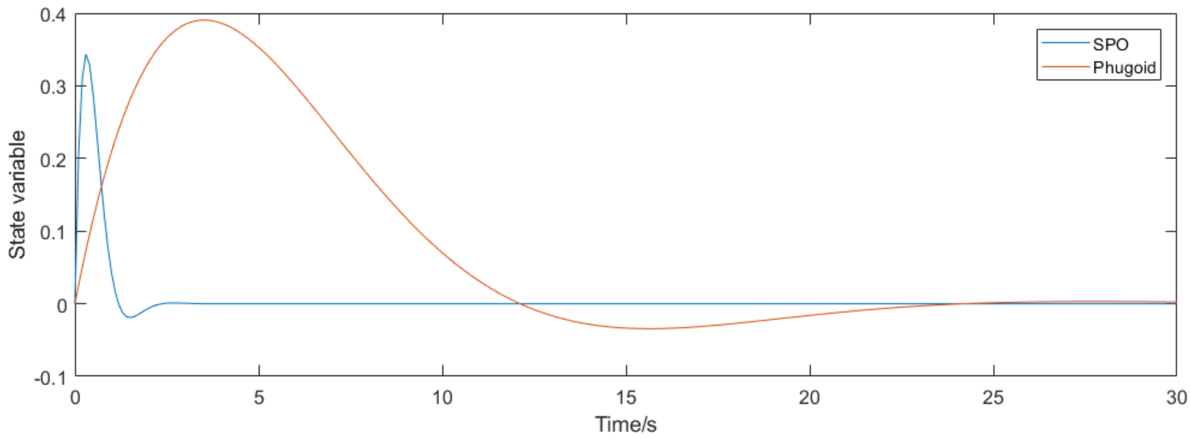

FIGURE 1.1: MATLAB output

jugate eigenvalues. The first pair $\lambda_{1,2} = -2.4352 \pm 2.6461i$ is the SPO mode. The decay rate (the real part) is much greater than the other pair $\lambda_{3,4} = -0.2006 \pm 0.2593i$ and so is the frequency (coefficient of i).

1.2 Mitigation of longitudinal dynamic modes

1.2.1 SPO regulations and qualification

The United States of America's Federal Aviation Authority regulates SPOs in FAR Part 23.181 [5] as follows: Any short period oscillation not including combined lateral-directional oscillations occurring between the stalling speed and the maximum allowable speed appropriate to the configuration of the airplane must be heavily damped with the primary controls -

(1) Free; and

(2) In a fixed position.

United Kingdom's Civil Aviation Authority regulates SPOs in a very similar manner and can be found in CAP482 S181.

The quality of handling is largely determined by pilot opinion. This is visualised by pilot opinion charts such as the one shown below.

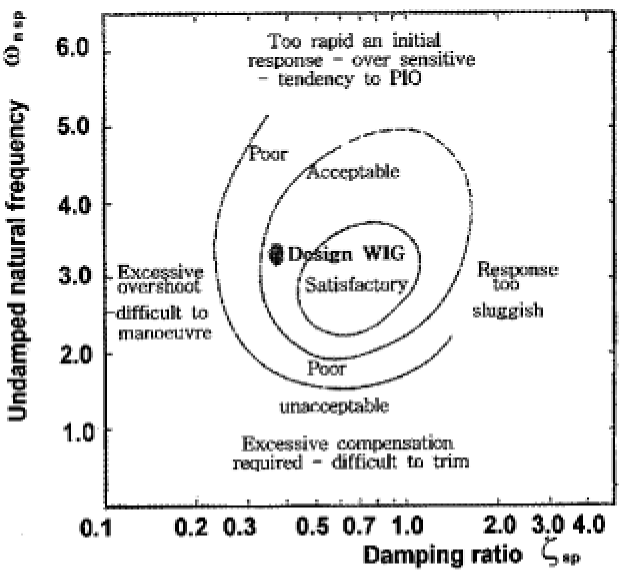

FIGURE 1.2: Short-period pilot opinion contours [3]

From SPO approximation [6] we can determine the natural frequency and damping ratio:

$$\omega_n = \sqrt{\mathring{Z}_w \mathring{M}_q + \mathring{M}_w \mathring{Z}_q}$$

$$\zeta = \frac{\mathring{M}_q + \mathring{Z}_w}{\omega_n}$$

Therefore, simply by adjusting the aerodynamic derivatives, it is possible to conform to the regulations. The regulations do not make the existence of a control system with a SPO dedicated model mandatory. This is most likely the reason why no such system exists. Thus, to fill this gap I will be developing a system that will focus on minimising the impact of SPOs.

1.2.2 Phugoid suppression

It is worth looking at how we deal with Phugoid oscillations first since suppressing phugoid oscillations has been well documented. This is achieved through the use of a Pitch Attitude Controller and has been described by Etkin in *Dynamics of Flight Stability and and Control* [2]. More recently, in the paper *Pitch Attitude Controller Design and Simulation for a Small Unmanned Aerial Vehicle* [4] a pitch-rate feedback control system was explored. In both cases, the control system did well to suppress Phugoid oscillations and managed to weaken SPOs but relied on gyroscopes or other attitude sensors. This meant that the control system took action AFTER the flight dynamics caused a deviation in the pitch rate/angle from the nominal. This model is currently the state-of-the-art, but includes an intrinsic lag between the onset of the oscillations and the corrective action of the controller.

There has been little development in designing a control system that detects the disturbance at the source and takes action BEFORE the flight dynamics can cause an appreciable change in attitude. In this project, I will aim to achieve a control system that does not wait for a large change in attitude to occur before acting. This will hopefully reduce the amplitude of the oscillation and the associated risks.

Chapter 2

Method

In this chapter, major design decisions and developing the tools required for this project will be discussed. There are for major decisions that need to be made: Pressure sensors, actuators, micro-controller, and the programming language.

2.1 Pressure sensors

There are a variety of sensors to choose from. There are absolute pressure sensors that simply measure the gauge or absolute pressure. Then there are pressure sensors that measure differential pressure. These have two ports and the sensor will measure the difference in pressure between them.

To calculate the lift on the wing, we will need to know the pressure distribution along the top and the bottom of the wing. A single differential pressure sensor can tell the difference in pressure at a certain chord position on the wing. For the same information, two absolute pressure sensors will be required. Furthermore, the airspeed in the wind tunnel will need to be measured. Using a differential sensor, one port can be subjected to the total/stagnation pressure from a pitot probe, and the second port will be subjected to the static pressure. The sensor will instantly give the difference between the two pressures which is the dynamic pressure. The airspeed can then be easily calculated using Bernoulli's principle:

$$V = \sqrt{\frac{2(p_0 - p)}{\rho}}$$

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Appendix A

High level

A.1 Low level