AERO50002 Flight Dynamics & Control

Aircraft Dynamics Assessment & Autopilot Design

1 Introduction

The flight dynamic characteristics of an aircraft are key in determining its handling qualities and by extension the level of ease and safety with which the vehicle can be operated. Furthermore, automatic feedback control is routinely employed in aircraft systems in order to improve their handling qualities or enhance the ease with which they can be operated by a pilot.

During the course of the Flight Dynamics & Control module we are discussing to great length the analytical modelling and estimation methods available to a designer for assessing the dynamical characteristics of an aircraft based on known inertial and aerodynamic properties. We will further introduce the fundamental operating principle of a PID feedback control system and the effect of each of the controller gains on the closed-loop response of a dynamical system.

We have however also highlighted the limitations of these methods and the need for testing of the physical system to ensure that our linear modelling fully captured the behaviour of what is inherently a non-linear system.

The objective of this series of experiments is therefore to

- predict the flight dynamics of an aircraft based on known aerodynamic and inertial data;
- assess the flight dynamics of an aircraft via flight testing and compare to analytical predictions;
- iteratively design a simple automatic controller for the aircraft based on an analytical model;
- test the performance of the automatic controller in flight and fine-tune as necessary.

2 The Aircraft

The flight tests will be conducted on a twin-jet executive aeroplane, the full size version and scale model of which you have previously flight tested and wind Tunnel tested as part of the Introduction to Aerospace module. Each of its medium bypass ratio turbofan engines is capable of producing an installed, static, sea-level thrust of 18,454 N. The thrust-line is 0.28 m above the aircraft's centre of gravity and aligned to the aircraft datum. The aircraft further features an all-moving tailplane without a separate elevator, so movements of the pilot's control column would alter the tail setting angle $-10° \leq i_H \leq 5°$. The horizontal tailplane volume coefficient $\overline{V}_H = 0.6722$ and its aerodynamic centre is 3.5 m above the datum. Note all angles are taken relative to the fuselage datum line, not to the zero-lift line.

Table 1: Aircraft Lifting Surface Characteristics

	Unit	**Wing**	**Tailplane**
Gross area	m^2	73.73	18.43
Span	m	20.95	9.31
Mean aerodynamic chord	m	3.79	2.04
Aspect ratio		5.93	4.74
Taper ratio		0.377	0.528
Dihedral (at trailing edge)	°	2	0
Geometric Twist	°	-3	0
Aerodynamic Twist	°	-3.5	0
Root sections		NACA 64_2-415	NACA 63_1-A012
Tip sections		NACA 64_2-412	NACA 63_1-A012

Table 2: Aircraft Inertial Characteristics

Maximum Takeoff Weight	24,398 lbs
Empty Weight	13,434 lbs
Max Fuel Weight	8,800 lbs
Longitudinal CG at Zero-Fuel Weight	10.14 m
Longitudinal CG of fuel tanks	10.06 m
Lateral CG of fuel tanks	0.61 m
Zero-fuel Roll Radius of Gyration	2.52 m
Zero-fuel Pitch Radius of Gyration	4.16 m
Zero-fuel Yaw Radius of Gyration	4.65 m
Zero-fuel I_{xz}/m	0.0117 m^2

Key geometric and inertial characteristics for the aircraft can be found in tables 1 and 2. All component vertical centres of gravity can be assumed to be at $z = 0$. The aerodynamic properties of the aircraft can be extracted from the wind tunnel and performance flight testing you conducted as part of the Introduction to Aerospace module's coursework.

3 Session 1 - Open-Loop Response

The first part of this series of experiments aims to analytically predict the dynamic response of the twin-engined business jet to external perturbations and to test the accuracy of the theoretical predictions through a flight test of the aircraft using the Department's flight simulators.

3.1 Preparatory Work

For a payload and fuel weight assigned to your group, calculate the inertial properties of your aircraft. You may assume that fuel mass acts as a point load at the centre of gravity of the fuel tanks, and that the centre of gravity always remains at $z = 0$ and on the aircraft's plane of symmetry.

Table 3: Asymmetric Dimensionless Stability & Control Derivatives

Coefficient	**Scaling Factor**	**Value**
$\mathring{Y}_V$	$0.5\rho U_e S_{ref}$	-0.5772
$\mathring{L}_V$	$0.5\rho U_e S_{ref} b$	-0.0723
$\mathring{N}_V$	$0.5\rho U_e S_{ref} b$	0.0773
$\mathring{Y}_p$	$0.5\rho U_e S_{ref} b$	0.0170
$\mathring{L}_p$	$0.5\rho U_e S_{ref} b^2$	-0.2228
$\mathring{N}_p$	$0.5\rho U_e S_{ref} b^2$	-0.0121
$\mathring{Y}_r$	$0.5\rho U_e S_{ref} b$	0.1312
$\mathring{L}_r$	$0.5\rho U_e S_{ref} b^2$	0.0782
$\mathring{N}_r$	$0.5\rho U_e S_{ref} b^2$	-0.0645
$\mathring{Y}_{\delta_A}$	$0.5\rho U_e^2 S_{ref}$	0.0000
$\mathring{L}_{\delta_A}$	$0.5\rho U_e^2 S_{ref} b$	-0.0763
$\mathring{N}_{\delta_A}$	$0.5\rho U_e^2 S_{ref} b$	0.0000
$\mathring{Y}_{\delta_R}$	$0.5\rho U_e^2 S_{ref}$	0.3090
$\mathring{L}_{\delta_R}$	$0.5\rho U_e^2 S_{ref} b$	0.0250
$\mathring{N}_{\delta_R}$	$0.5\rho U_e^2 S_{ref} b$	-0.1117

For the weight, altitude and indicated airspeed assigned to your group, calculate the stability derivatives of you aircraft. The longitudinal derivatives can be calculated analytically, using the methods derived in class, and you may assume that thrust effects are negligible.

The asymmetric stability derivatives are given in dimensionless coefficient form in table 3, having been calculated using a potential flow solver and applying appropriate empirical corrections[1] for viscous effects and the presence of the fuselage.

[1] A vortex-lattice code, with sectional viscous drag corrections, and EDSU datasheets 83026, 73006 and 79006 were used.

Having calculated the dimensional value of the stability derivatives, use the equations of motion, linearised about an equilibrium of wings-level, constant altitude flight, to predict the dynamic modes of the aircraft.

- For each of the dynamic modes calculate the time to half/double amplitudes, and (if oscillatory) the period of oscillation expected.
- Compare the predictions obtained by analysing the complete system of equations to those obtained using the simplified, reduced-order systems, discussed in class. How well did our approximations work?

Optional Extra:

In addition to performing an eigenvalue analysis of the system, you can use Simulink to simulate the response of the system to some prescribed control inputs.

i To do so, first derive expressions for the elevator (rad) and throttle (%) control derivatives of the aircraft. The aileron (rad) and rudder (rad) control derivatives are provided in dimensionless form. Evaluate the control derivatives at your aircraft's equilibrium conditions. (You will have to do it for the prep work of the next lab anyway)

ii Populate the `LinearEoM` scripts inside the `linearLong.slx` and `linearLatDir.slx` simulink files provided.

iii Adjust the switches (by double-clicking or adjusting the mode) to select which mode you would like to excite using the pre-defined control inputs.

iv Open the scope by double clicking on it and press the Run button.

3.2 Experimental Method

The experimental setup comprises of a flight simulation station, running X-Plane 10. The operator can control the aircraft by actuating the horizontal stabilator, ailerons, rudder and throttle output. The aircraft can be trimmed in pitch by adjusting a trim wheel which also controls the tail setting angle.

Each group will be assigned one of the static simulator stations to use. Only two members of your group can be in the simulator area at any time, acting as the pilot and flight engineer. The rest of the group members will be able to observe from the mezzanine where a real-time feed of data will be provided. You should plan on splitting the work equitably among all members of your group.

The flight simulation stations are connected, via a Local Area Network connection, to a data acquisition program running on the instructor's PC. The data acquisition program is implemented in Simulink and provided as `dataRecorder.slx`. The control surface deflections are all given as a percentage in the max deflection of the surface in that direction. Furthermore the stabilator deflection provided by X-Plane is defined as positive when resulting in a nose-up motion of the aircraft, ie opposite to our definition in class notes, and the stabilator deflection associated to the trimmer will not be recorded. The aileron and rudder control inputs are defined positive for a right stick or right rudder control input respectively.

A Matlab script for post-processing the data acquired, `dataExtractor.m`, is also is also provided. Complete instructions on using the data acquisition system are provided as an appendix. *Note that due to the high sample rates required for some modes, file sizes can be of the order of several GB, therefore groups are advised to bring a USB stick with them to retrieve their dataset*

Trimming the Aircraft

Testing the dynamic response of an aircraft requires the aircraft to be in an initial wings-level trimmed state. For these test we will additionally require a near constant altitude flight be achieved and no initial control input. The latter requirement is simply a matter of convenience for the conduct of our later tests. To trim the aircraft the following procedure should be followed:

a) Set the required amount of fuel and the offset for the aircraft's zero-fuel centre of gravity position from the instructor's console

b) Climb/descend to roughly the desired altitude. Try to maintain near your target level flight speed in the climb/descent, thus reducing the need for subsequent speed adjustments.

c) Apply a reasonable level of throttle and adjust the stick input, and therefore aircraft pitch, to maintain your altitude.

d) As the aircraft speed settles, further adjusting the throttle setting to accelerate/decelerate to the desired airspeed. As velocity changes, remember to adjusting the pitch attitude to remain level.

e) Continue the process until the desired constant airspeed and altitude are reached

f) Once the aircraft is in the desired equilibrium state, we must adjust the trim wheel such as to achieve stick-free equilibrium, thus relieving the need any pitch control input. Work iteratively, making small adjustments of the trim wheel in the required direction, reducing the stick deflection required to maintain level and repeat until no pitch control input is required.

Exciting the Phugoid mode

The Phugoid mode is an oscillatory mode where the pitch attitude and velocity states are dominant. It has a high period of oscillation and light damping. Starting from a stick-free trimmed, level flight condition:

a) Record the velocity, altitude and fuel weight of your aircraft in the trimmed condition. Start the Simulink data recorder and note the start time.

b) Gently pull back on the stick until the aircraft's pitch attitude has increased by about 5° and the aircraft enters a decelerating climb.

c) Maintain the back pressure until the aircraft's indicated airspeed has decreased by about 10 kn.

d) Release the stick and allow the Phugoid mode to evolve.

e) Once sufficient data has been collected, stop the data recording and note the end time.

f) To get the aircraft back to its equilibrium condition, apply appropriate pitch control. No significant change in trim should be required if returning to the original altitude and airspeed if no significant change in fuel weight has occurred.

Exciting the SPPO

The Short Period Pitching Oscillation is a coupled pitch-rate and angle of attack motion, of high frequency and high damping. Starting from a stick-free trimmed, level flight condition:

a) Record the velocity, altitude and fuel weight of your aircraft in the trimmed condition. Start the Simulink data recorder and note the start time.

b) Apply a moderate nose down pitch input (about half stick deflection) followed by an equal nose up input and then release the controls. Using the same magnitude and rate of actuation both nose up and down will ensure no net change in pitch and thus avoid also exciting the Phugoid mode.

c) Once sufficient data has been collected, stop the data recording and note the end time.

Exciting the Roll Subsidence mode

The Roll Subsidence mode is a non-oscillatory damping response of the aircraft's rolling motion. Starting from a stick-free trimmed, level flight condition:

a) Record the velocity, altitude and fuel weight of your aircraft in the trimmed condition. Start the Simulink data recorder and note the start time.

b) Apply a full right or full left stick input. Once the aircraft reaches a constant roll-rate, release the stick.

c) Once sufficient data has been collected, stop the data recording and note the end time.

d) Apply aileron and elevator control as required to return the aircraft to its original trimmed state.

Exciting the Spiral Mode

The Spiral mode is a non-oscillatory mode where the roll angle of the aircraft couples with its yaw rate. Starting from a stick-free trimmed, level flight condition:

a) Record the velocity, altitude and fuel weight of your aircraft in the trimmed condition. Start the Simulink data recorder and note the start time.

b) Apply a partial right rudder input such that the aircraft yaws and rolls to the right. Once the aircraft reaches a roll angle of about 10° bank, release the rudder pedal.

c) Wait until the roll angle has approximately halved or doubled. Once sufficient data has been collected, stop the data recording and note the end time.

d) Apply aileron and elevator control as required to return the aircraft to its original trimmed state.

e) Repeat with a left rudder input to investigate the left turning spiral response.

Exciting the Dutch Roll mode

The Dutch Roll mode is a coupled roll-rate, yaw-rate and side-slipping oscillatory motion.Starting from a stick-free trimmed, level flight condition:

a) Record the velocity, altitude and fuel weight of your aircraft in the trimmed condition. Start the Simulink data recorder and note the start time.

b) Apply a partial right rudder input such that the aircraft yaws and rolls to the right followed by an equal and opposite left rudder input, bringing the aircraft's wings back to level. The two inputs should be in rapid succession of about 1-2 seconds each, such that a large enough roll and yaw rate develops.

c) Once sufficient data has been collected, stop the data recording and note the end time.

3.3 Data Analysis

Having recorded time history data for the response of the aircraft in each of its dynamic modes, they can be analysed to extract the frequency of oscillation and damping ratio. A rather simple method requires you to plot your data for that state and

- for oscillatory motions, measure the period of oscillation T, i.e. the time required for one of the dominant states to oscillate from peak amplitude to peak amplitude. The radial frequency of oscillation is then

$$\omega_d = \frac{2\pi}{T}.$$

Furthermore measuring the amplitude of two peaks $A(t)$ and $A(t + nT)$ you can approximate the damping ratio as

$$\zeta = \frac{1}{\sqrt{1 + \left(\frac{2\pi}{\delta}\right)^2}}$$

where δ is the logarithmic decrement

$$\delta = \frac{1}{n} \ln \frac{A(t)}{A(t + nT)}.$$

The undamped natural frequency of the mode is then

$$\omega_n = \frac{\omega_d}{\sqrt{1-\zeta^2}}$$

and the pair of eigenvalues characterising that mode can then be approximated as

$$\lambda_{1,2} = -\frac{\omega_d\,\zeta}{\sqrt{1-\zeta^2}} \pm i\,\omega_d.$$

- for non-oscillatory modes, the eigenvalue can be approximated by picking two points $A(t)$ and $A(t+\tau)$ and using
$$\lambda = \frac{\ln\left(\frac{A(t+\tau)}{A(t)}\right)}{\tau}.$$

Note that these "graph-based" approaches are quite susceptible to the effects of experimental uncertainty and signal noise, and therefore should be repeated using several different pairs of points. An alternate, somewhat more robust, yet more complex method requires the use of non-linear regression tools, such as Matlab's `nlinfit()`, to fit the acquired data to the equations

$$A(t) = C + A_0 e^{rt}\sin(st+\tau),$$

where C, A_0, s r and τ are unknown constants, for an oscillatory mode and

$$A(t) = C + A_0 e^{rt},$$

where C, A_0 and r are unknown constants, for a non-oscillatory one. You should always confirm the results obtained using this approach with those from the graphical method to ensure their validity.

Based on the above results, compare the frequency and damping characteristics of the modes you predicted to those measured. Consider what the sources for any discrepancies observed might have be.

4 Session 2 - Autopilot Design

Having characterised the flight dynamics of the aircraft, and to some extent validated your analytical model, we can proceed to design an automatic controller for the aircraft. The three most utilised functions of an autopilot are the wings-level hold, velocity-hold and attitude-hold, which combined allow the aircraft to be set in any desired level or climbing flight condition.

For this laboratory session you will design a feedback control system capable of performing each of the three function in isolation and subsequently combine them into a single system for testing on the actual aircraft, being flown in the flight simulator. Proportional-Integral-Derivative feedback controllers will be used for their versatility and ease of implementation.

4.1 Preparatory Work

In order to tune the three controllers' gains, we must first derive the control derivatives of our symmetric and asymmetric state-space systems. To do so, first derive expressions for the elevator (rad) and throttle (%) control derivatives of the aircraft. The aileron (rad) and rudder (in rad) control derivatives are provided in dimensionless form in Table 3. Evaluate the control derivatives at your aircraft's equilibrium conditions.

We will be using Simulink to simulate the vehicle's dynamics and implement the PID feedback controllers. To do so, first populate the `LinearEoM.m` scripts inside the `linearLong.slx` and `linearLatDir.slx` Simulink files provided. You should check that your Simulink models accurately represent the vehicle's predicted dynamics by adjusting the switches (by double-clicking or adjusting the mode) to select which mode you would like to excite, using the pre-defined control inputs, and comparing the vehicle's simulated open-loop repsonse to that predicted for the first part of this experiment.

Note that while, for this exercise, we have made use of the predicted dynamics of the vehicle in order to tune the PID controller gains, the same steps can be followed using a state space model stemming from measurements of the actual system. You would simply have to reverse develop a model for the system's dynamics from the fight test data previously gathered using tool such as Matlab's System Identification App, in a manner similar to that which you are applying for the Mechatronics module laboratories.

Roll Angle Controller

To implement a PID feedback controller for the aircraft's roll angle Φ, follow the following steps:

- Open the `linearLatDir.slx` Simulink model you previously populated and validated.
- We want to add a PID feedback controller that generated an aileron control command, as a faction of max deflection, based on the error between a setpoint for the roll angle and the actual roll angle (in degrees). To do so you must:
  - i. first remove the connection between the control input switch and the `u` channel input of your lateral dynamic model.
  - ii. Add a Demux block to split the 2 element input vector `u` into individual aileron and rudder control signals. If not already set, double click on the block and set the number of outputs to two.
  - iii. Add a Mux block to re-combine the two control signals into a single vector output.
  - iv. Connect the second output of the demux block to the second input of the Mux block, as the PID controller will not affect the rudder command.
  - v. Create a Step, a Subtract and a PID Controller block.
  - vi. Connect the Step source to the '+' terminal on the Subtract block and connect its output to the PID block's input.

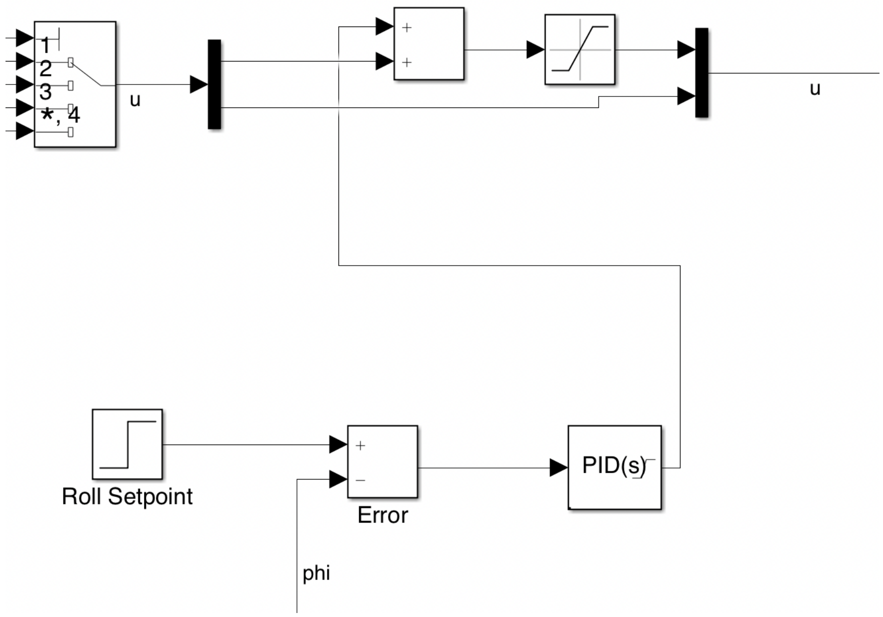

Figure 1: Blocks to be added in implementing a PID feedback roll angle controller

vii. Place an Add block and a Saturation block between the first output of the Demux and first input of the Mux blocks. Connect them in series. Connect the PID block output to the other input of the Add block. This will combine any predefined control inputs with those generated by the PID controller. The saturation block must be defined to output values between -1 and 1.

viii. Connect the "-" terminal of your Subtract block to the `phi` state output of your model going into the scope. The subtract block will therefore calculate your error term to drive the PID.

The resulting block diagram should now look like the one shown in figure 1.

- Double-click on the Step Block and make sure both the initial and final values are zero. You can modify this as you test your gains to see the response to a step change in the setpoint.

- Double-click on the PID block and select PD, continuous-time as the type of controller. Unless you wish your controller to act as an aileron trimmer, countering any lateral asymmetries in the aircraft, no integral term is required. Set the controller's output limits to -1 and 1.

Investigate the effect of the Proportional and Derivative gains on

i. the closed-loop system response to a step change change in the setpoint;

ii. the closed-loop system response to an external perturbation. In this case use the Spiral or Dutch Roll mode triggers implemented in the Simulink model. You can alternatively change the initial conditions for the simulation inside the $1/s$ integrator block, to define an initial perturbed state.

Start by determining the sign of the proportional gain required, so as to reduce a positive error. Reviewing the sign of the L_{δ_A} derivative can help. Then roughly estimate the proportional gain as the value that would result in a full aileron deflection (± 1) when the error exceeds some given roll angle, say 20-30 degrees. If you find that a faster or slower response is desirable, adjust the proportional gain accordingly.

Once satisfied with the speed of the system's response, start increasing the magnitude of the Derivative gain in order to reduce any overshoot or damp any oscillatory behaviour.

Pitch Attitude & Velocity Hold

To implement a PID feedback controller for the aircraft's climb angle and velocity open the `linearLongDir.slx` Simulink model you previously populated and validated.

Modify the Simulink model to add two PID controllers. One to command the elevator deflection, as a fraction of the maximum positive deflection of 5 degrees, based on the error between the the aircraft's target and actual climb gradient (in deg). And one to command the engine throttle, as a percentage of max thrust output, based on the error between the target and actual velocities (in knots). The instantaneous climb gradient can be computed using the aircraft's states as

$$\gamma' = \Theta' - \tan^{-1}\left(\frac{W'}{U_e + U'}\right).$$

Table 4: Typical effect of gains on the closed loop response of the system

	Rise Time	Overshoot	Settling Time	Steady State Error
P	Decrease	Increase	Little effect	Decrease
I	Decrease	Increase	Increase	Eliminate
D	Little effect	Decrease	Decrease	No effect

As with the roll controller, first tune each PID controller separately, keeping the other's gains to zero. A useful initial approach to tune your PID controller is to:

- Set all gains to zero initially, then
- increase the proportional gain term until a reasonable rise time is achieved, then
- increase the derivative gain in order to decrease the overshoot, settling time and amount of elevator deflection required, then
- increase the integral gain to eliminate any steady state error.

Test your aircraft's response to external perturbations by changing the initial condition for the aircraft's U velocity or pitch attitude Θ, or to step changes in the target velocity or pitch attitude. Ensure the aircraft has a reasonable rise time and is well behaved.

Once each controller has been tuned in isolation, test the system with both controllers active. As before, test the closed loop response to a change in the setpoint or external perturbations. How has the use of two PID controllers in parallel changed the system's behaviour? Make note of your selected gains in preparation for the lab session.

4.2 Experimental Method

The experimental setup comprises of a flight simulation station, running X-Plane 10. The operator can control the aircraft by actuating the horizontal stabilator, ailerons, rudder and throttle output. The aircraft can be trimmed in pitch by adjusting a trim wheel which also controls the tail setting angle.

Each group will be assigned one of the static simulator stations to use. Only two members of your group can be in the simulator area at any time, acting as the pilot and flight engineer. The rest of the group members will be able to observe from the mezzanine where a real-time feed of data will be provided. You should plan on splitting the work equitably among all members of your group.

The flight simulation stations are connected, via a Local Area Network connection, to a data acquisition and control program running on the instructor's PC. The data acquisition and control program is implemented in Simulink and provided as `SimControl.slx`. It operates by receiving data from the aircraft's onboard sensors as well as the instantaneous pilot control inputs, given as fractions of the maximum deflection. Remember that unlike the definition in lectures and in your theoretical model, the stabilator deflection in the flight simulator is defined as positive when resulting in a pitch-up response.

Two PID and one PD feedback controllers, controlling the aircraft's velocity (in knots IAS), climb gradient (in degrees) and roll angle (in degrees) respectively, have been implemented. The automatic controller commands are combined with the control input and sent back to the flight simulator using UDP over the Local Area Network.

You can define the setpoint for each of the three controllers using the sliders provided and activate/deactivate them using the switches provided. Note that **once the Simulink program starts running, the flight simulator will expect all further control inputs to originate form the remote computer and you should therefore not stop Simulink running until all your tests have been completed and all data has been gathered**.

The Simulink code further features a data acquisition block which can be started/stopped using the ON/OFF switch provided. A Matlab script for post-processing the data acquired, `dataExtractor.m`, is also is also provided. Complete instructions on using the data acquisition system are provided as an appendix.

The procedure for testing the performance of your controllers, installed on the actual aircraft is provided below. It is recommended that you test each of the three controllers in pairs, such that all group members get to have a go.

- Start the Simulink script and press run. Make sure that all controller switches are OFF and the aircraft is responding to stick control inputs passing through.
- Trim the aircraft in a steady, level flight flight condition, as prescribed for your group (for part 1).
- Define the setpoint for each of the controllers to your group's flight conditions above.
- Test the performance of your controller (following the relevant instructions below) and further tune as necessary.
- Pause the simulation, by pressing the Pause button on the X-Plane instructor console, and stop the Simulink script
- Find the `.mat` file where your data was recorded and rename it using a relevant file name. Do not skip this step as the file will be overwritten when you run the Simulink script again for your next test.
- Swap operators as necessary for the next test. Run the Simulink script, resume the operation, and repeat the steps above.

To maximise your testing time during the lab session, you should download the template `SimControl.slx` *Simulink code available on Blackboard prior to the lab, adjust the controller gains to your desired values (remembering that gains are dimensional), and edit the* `.mat` *output filename, found inside the Sensors → Recorder blocks to one unique to your group. You may also wish to add a scope to the model so as to plot the variation of key states and control inputs in real time.*

Roll Controller Testing

- Activate the roll controller and ensure it is able to maintain the aircraft in a wings-level condition.
- Test and record the response of your controller to roll perturbations by actuating the rudder pedals.
- If the response observed is not satisfactory, adjust the controller gains to improve the roll controller's performance. Repeat until a satisfactory response is observed.
- Test and record the response of your controller to a $\pm 10°$ step change in the setpoint for the roll angle.
- With the roll controller still active, so as to help maintain wings-level flight, re-trim the aircraft at the prescribed conditions.

If the performance of your roll controller was deemed satisfactory, you can keep it on for the following two tests, thus reducing pilot workload. It is safe to assume that automatic aileron control inputs will have a minimal effect on your pitch and velocity.

Pitch Attitude Controller Testing

- Activate the Pitch Attitude controller (disengage the speed controller if previously on) and ensure it is able of maintain the aircraft in a level flight condition.
- Test and record the response of your controller to a change velocity by adjusting the throttle.
- If the response observed is not satisfactory, adjust the controller gains to improve the climb gradient controller's performance. Reset the aircraft to a trimmed level flight condition and repeat until a satisfactory response is observed.
- Test and record the response of your controller to a change in the climb angle, by setting it to a target value of $+5°$.
- If the response observed is not satisfactory, adjust the controller gains to improve the pitch controller's performance. Repeat until a satisfactory response is observed.

Speed Controller Testing

- Activate the speed controller (disengage the pitch controller if previously on) and ensure it is able of maintain the aircraft in a steady level flight condition.
- Test and record the response of your speed controller to a change in climb gradient by pulling up slightly.
- If the response observed is not satisfactory, adjust the controller gains to improve the speed controller's performance. Reset the aircraft to a trimmed level flight condition and repeat until a satisfactory response is observed.
- Finally test and record the response of your controller to a change in the target velocity, by increasing the target speed value by 5 kn IAS.
- If the response observed is not satisfactory, adjust the controller gains to improve the pitch controller's performance. Repeat until a satisfactory response is observed.

Full Autopilot Testing

- Set the aircraft to a steady level flight condition and activate both the speed and pitch attitude controllers.
- Test and record the response of your controller to a change in the climb angle setpoint.
- If the response observed is not satisfactory, adjust the controller gains to improve performance. Repeat until a satisfactory response is observed.

5 Assessment

This laboratory exercise will be summatively assessed through a short written coursework submission. Its deadline will be two weeks after your final lab session (i.e. 11pm Monday or Thursday). The coursework will address the following points.

- How good were your initial predictions for the aircraft's flight dynamics? What might the source of any discrepancies be?
- What approach did you take in tuning your controllers? Why did you pick the specific scenarios? Why were these values for gains chosen?
- How well did your controllers perform on the actual aircraft? What adjustments did you have to make and why?
- What effect did a change in velocity have on the performance of your controllers? Why might that be and how could it be addressed?

You will further be require to support these points by presenting

- A plot of predicted and actual system response with time for each of the aircraft's five dynamic modes.
- A table of the predicted and actual levels of damping, frequencies of oscillation and times to half/double amplitude for each of the aircraft's five dynamic modes.
- A table of your chosen gains for each controller, based on tuning using the theoretical model, and their final values, following tuning on the actual aircraft.
- A plot of the predicted response of your controllers to each of your tuning scenarios.
- A plot of the actual aircraft's response due to step changes in the controller setpoint for roll angle, climb gradient and velocity.

See the answer sheet provided for the full list of the questions that you are required to answer. Your answers will be assessed based on the following criteria:

- The accuracy of your predicted stability derivatives and resulting simulations.
- The analysis of your experimental results to estimate the mode's characteristics.
- The quality of the plots presented, including whether all relevant states needed to support you discussion are presented, whether scaling used allows for comparisons between plots and whether appropriate labels, fonts etc are used.
- The clarity and correctness of the arguments or rationale you present when discussing your findings or approach to the lab work.
- How reasonable the values you obtained for your tuned gains are.