**Flight Dynamics & Control**

**Aircraft Dynamics Assessment and Autopilot Design Exercise**

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| Group Number | 07 | Student CIDs | 02488088, 02200298, 02464991  02376386, 02383703, 02402843 |

**Answer the following questions within the space provided using 11pt Arial. Make sure tables and figures are properly formatted and readable. Marks will be deducted for bad formatting.**

Define the conditions under which your tests were conducted. A single altitude, flight speed and loading should have been used for all computations and tests

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| --- | --- | --- | --- |
| Flight Speed (IAS), kt | **190** | Payload weight, lbs | **500** |
| Altitude, ft | **9000** | Fuel weight, lbs | **2400** |
|  |  | CG offset, inch | **+0.77** |

**Q1.** Provide dimensional values for the following inertial properties, stability and control derivatives computed.

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| --- | --- | --- | --- | --- | --- |
| ,kg m2 | 47049.9 | , kg m2 | 128216.8 | , kg m2 | 169200.7 |
| ,kg m2 | 86.7 | , m | 10.1282 |  |  |
| ,Ns/m | -104.3 | , Ns/m | -345.4 | , Ns | 1712.5 |
| ,Ns/m | 526.6 | , Ns/m | -19961.8 | , Ns | -16823.8 |
| ,Ns/rad | -4814.2 | , Ns/rad | -12688.7 | , Ns/m rad | -311915 |
| , Ns2/m | -22.0 | , Ns2/m | -154.5 | , Ns2 | -1654.2 |
| , N/rad | -85102 | , N/rad | -619141 | , Nm/rad | -5860451 |
| , N | 18454 | , N | 0 | , Nm | -5167 |

Note that in the table above are the throttle derivatives given per % throttle.

**(10% of marks)**

**Q2.** Present your simulation and experimental findings for the aircraft’s open-loop response by plotting the variation of the most relevant states of the phugoid, SPPO, roll subsidence, spiral and Dutch Roll modes. Present them side-by-side and scale the magnitude of your computational results as to allow a direct comparison with the experimental cases. *(Provide plots only)*

**EXPERIMENTAL SIMULATION**

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| Phugoid  A graph of different types of pharmacology  AI-generated content may be incorrect. |
| SPPO A graph of different types of data  AI-generated content may be incorrect. |
| Roll Subsidence  A graph of a roll of paper  AI-generated content may be incorrect. |
| Dutch Roll  A group of graphs showing different types of data  AI-generated content may be incorrect. |
| Spiral  A graph of different types of curves  AI-generated content may be incorrect. |

**(10% of marks)**

**Q3.** Provide your computed and experimentally derived values for the eigenvalues of each dynamic mode

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| --- | --- | --- | --- | --- | --- |
|  | Experimental Period, s | Exp Time-to- half/double amplitude, s | Experimental Eigenvalue | Theoretical Eigenvalue | Reduced-order model Eigenvalue |
| Phugoid | 57.8030 | 11.6691 | -0.0594 ± 0.1087 i | -0.0059 ± 0.1422 i | -0.0044 ± 0.1371 i |
| SPPO | 1.0166 | 0.1933 | -3.5858 ± 6.1806 i | -3.6038 ± 3.3523 i | -2.8191 ± 2.6548 i |
| Roll Subsidence |  | 0.0766 | -9.0459 | -9.1834 | -7.6572 |
| Dutch Roll | 1.8026 | 0.3514 | -1.9724 ± 3.4856 i | -0.5453 + 2.2611 i | -0.4517 ± 1.8890 i |
| Spiral |  | 23.7379 | 0.0292 | 0.0066 | 0.0074 |

**(10% of marks)**

**Q4.** Discuss the quality of your predictions compared to your experimental findings. What might the source of any discrepancies between your computed values and those observed during flight testing be? *Briefly* highlight any issued that may have impacted your experimental values.

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| For the Phugoid mode, the imaginary parts of eigenvalues were consistent across methods, with experimental values deviating by 26% and 30% from reduced-order and theoretical findings, respectively. Theoretical and reduced-order models predicted larger imaginary parts and shorter oscillation periods. Real parts varied, with reduced-order models predicting lower damping, while experimental damping was 10 times higher than theoretical, indicating more prominent damping in experiments. Experimental eigenvalues were determined using a discrete peak method, ensuring consistency across tests. Theoretical models neglected fuselage effects, contributing to damping differences.  For SPPO, theoretical and reduced-order findings aligned closely, suggesting reasonable predictions, but experimental values had a higher imaginary part. Real parts were negative across all methods, confirming a stable mode. Experimental real parts deviated by 21% and 5% from reduced-order and theoretical results, respectively. The imaginary part differences suggest oscillation period variations, likely due to control input timing, especially with manual stick control. Automated input responses or varying pitch amplitudes could improve accuracy.  Roll Subsidence showed consistent eigenvalues across methods, indicating a heavily damped, non-oscillatory mode. Reduced-order models under-predicted damping but remained within the same order of magnitude as theoretical results. Experimental real parts differed by 15% and 2% from reduced-order and theoretical values, respectively. Discrepancies arose from rudder miscalibration, as confirmed by consistent mode graphs.  Dutch Roll was stable with damped oscillations, as indicated by negative real and nonzero imaginary parts. Experimental results showed significantly higher damping, with real parts differing by an order of magnitude from theoretical predictions. Imaginary parts deviated by 46% and 35% from reduced-order and theoretical values but remained within the same order of magnitude. The mis-calibrated rudder pedals likely influenced discrepancies. Theoretical models also disregarded fuselage effects, contributing to damping differences.  The only mildly unstable non-oscillatory mode was Spiral, with positive real eigenvalues across all methods. While magnitudes were reasonable, experimental values were an order of magnitude higher than theoretical and reduced-order results. This was likely due to excessive rudder displacement from miscalibration. |

**(20% of marks)**

**Q5.** Briefly describe the approach your group took when tuning your controller. What scenarios did you consider and what were your tuning targets (for example rise time, settling time).

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| The PID tuning was conducted using a combination of Simulink's PID tuning toolbox and manual iterative gain adjustment. This process aimed to prioritize physically reasonable rise times, minimal overshoots, suitable disturbance rejection, and high degrees of robustness. The airspeed controller should result in a conservative rise time, as this allows the controller to handle the engine's (unknown, yet non-negligible) spool up time. For similar reasons, this controller must be designed to avoid either max or idle throttle. As such, the tuning process revolved around ensuring that no minimal throttle variation is applied for a stepped 5 knot velocity increase (tuned with the climb controller active, as to hold a constant alt.) . There is little practical need for extremely rapid changes in velocity, especially for such small deviations away from the equilibrium cruise velocity. On the other hand, the bank angle controller is expected to be significantly more responsive. Considering that rolling motion is heavily damped, this enables for very quick rise times to be achieved, with very quick settling times. This controller was tuned in regards to a 10 degree bank angle step input. Finally, the climb gradient controller should be developed with a heavy emphasis on robustness, this is because the model parameters (and the control derivatives) have the greatest uncertainty. This controller needs to perform well, even if the calculated stability derivatives do not accurately reflect the motion of the flight sim.  The rise time should be fairly rapid, yet to a lesser extent than the roll controller. This controller was tuned in regards to a +5 degree climb angle step input. |

**(5% of marks)**

**Q6.** Provide your PID gains for each of the three controllers your designed. Remember that gains are dimensional and here define the percentage input per degree or knot of measured error.

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| --- | --- | --- | --- |
| Controller input varies from 0 to 1. | Proportional Gain | Integral Gain | Derivative Gain |
| Roll | **0.06 (deg-1)** | **0.039 (deg-1s)** | **0.006 (deg-1s-1)** |
| Climb Angle | **0.290 (deg-1)** | **0.051 (deg-1s)** | **0.052 (deg-1s-1)** |
| Speed | **0.138 (kts-1)** | **0.007 (kts-1s)** | **-0.148 (kts-1s-1)** |

**(5% of marks)**

**Q7.** Present your simulation and experimental findings for your initial autopilot’s closed-loop performance by plotting the variation of the most relevant states. Present them side-by-side, using equivalent perturbations and scale the magnitude of your computational results as to allow a direct comparison with the experimental test cases. *(Provide plots only)*

**EXPERIMENTAL SIMULATION**

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| --- |
| Roll Controller  A graph of a graph  AI-generated content may be incorrect.A graph of a graph |
| Climb Angle Controller  A graph of a graphA graph of a graph |
| Speed Controller  A graph of a graph |

**(10% of marks)**

**Q8.** For each of your controllers briefly describe how you re-tuned their gains based on the responses observed during your testing. Provide the final tunned gains. Present a plot of the final performance of your final standalone controllers to a step change in the setpoint.

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| Roll Controller  This controller yielded good performance. Overshoots were generally minimal, the rise time and settling time were physically reasonable. Initial technical difficulties meant that a significant portion of the lab was spent restarting XPlane; as such, the remaining two controllers were prioritized.  Though, a feasible improvement to this controller would be increasing the derivative gain, to shrink the settling time and to reduce overshoot further.  Initial Gains Retained |
| A graph with text and numbersClimb Angle Controller: The initial gains were associated with large quantities of overshoot, as evidenced by the aggressive initial pitching behaviour. In order to reduce overshoots, the proportional gain was reduced incrementally. When a more reasonable response was observed, the derivative gain was increased slightly to further decrease overshoot and to decrease settling time. Had this process been continued further, a more favourable response would have been obtained, there was still significant overshoot by the end of the lab.  Kp = 0.06 Ki = 0.051 Kd = 0.1 |
| A graph of a graphSpeed Controller: Because the commanded change in velocity was of a relatively small nature, assessing the behaviour of the controller was difficult to perform by simply looking at aircraft’s instruments. Moreover, the assessed performance of this controller is highly dependent on holding a constant pitch, making it difficult to discern the nature of small airspeed fluctuations. When an slight increase in velocity is commanded, fluctuations of no more than 0.3 m/s are witnessed. For this reason, along with time constraints, the controller was left as is.  Initial Gains Retained |

**(15% of marks)**

**Q9.** How well did the control gains tuned using your theoretical model perform during flight testing? What might the source of any observed differences in their performance be?

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| The predicted control gains performed well as initial guesses; all of them resulted in a stable closed-loop system. The roll controller performed well, both when it came to holding a set point and disturbance rejection, the initial PID guesses resulted in minimal overshoots, and steady-state error was largely eliminated. The lateral equations of motion were primarily populated with stability and control derivatives from an empirically corrected VLM simulation; these values likely correspond to the aircraft’s behaviour in the flight sim with a high degree of accuracy.  The initial airspeed controller gains performed decently, this ultimately stems from having accurate estimates of the thrust-related control derivatives; the thrusting forces are well defined and appear to correspond linearly with the application of throttle.  The climb gradient controller performed poorly with the initial guesses; it was extremely prone to overshoots. As such, the proportional gains were incrementally decreased until this behaviour improved, the derivative gains were subsequently increased slightly as well. The longitudinal stability and control derivatives were sourced from an amalgamation of wind tunnel and flight sim data. This data is fundamentally inconsistent in the way the plane’s aerodynamics are modelled. Most of the data regarding the tailplane is sourced from wind tunnel testing, but this data is heavily dependent on the upstream flow field, which possesses complexities not accurately captured by XPlane’s blade element simulations. These simulations lack complete representations of 3D flow effects and often struggle to model wake behaviours. In particular, the tailplane’s downwash characteristics, as well as its lift and drag curve slopes, likely differ significantly from the wind tunnel tests. This may have resulted in underestimating the elevator’s control derivatives, or overestimating the tailplane’s contribution to longitudinal damping; both of which could’ve lead to the observed flaws in the initial proportional gains |

**(10% of marks)**

**Q10.** Plot your combined pitch and velocity autopilot’s response to a change in the climb angle setpoint. Did you have to adjust the gains to ensure satisfactory performance?

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| Only the throttle controller mandated any form of gain adjustment, the proportional gain was increased from 0.138 to 0.2 to reduce rise time. The integrator constant (Ki) was increased from 0.007 to 0.05 with the intention of more proactively mitigating steady state error and further reducing rise time. The initial gains for the throttle controller were developed with the goal of preforming well in regard to a step change in the velocity setpoint, assuming wings level, zero-climb conditions. As such, this controller proved to be slightly lacklustre when it comes to maintaining a given airspeed in a not-so-shallow climb (such as the commanded 9 degree climb setpoint featured above). The remaining two controllers were left as is. |

**(5% of marks)**