THE UNIVERSITY OF SYDNEY

AERO4560 FLIGHT MECHANICS 2

Assignment 3, 2020

Submit via Canvas by 23:59 Friday 20 November 2020.

This assignment builds on the analyses performed in Assignment 1 and 2. The objective is to design a complete autopilot, to investigate the stability and performance of the control system, and study the change in response of the aircraft to gust inputs. The design is to be done using Bode and Root Locus design methodologies (see *sisotool*).

Ensure that you illustrate your control loop topologies, and that you write down and explain how you have formulated your closed-loop transfer functions. Ensure that all transfer functions presented are given *in zero-pole-gain form*. Submit your m-files *as an appendix* to your report.

This assignment is worth 40% of the course. *You are to work in four separate groups, with each group considering a different aircraft. Within each group, half the members will consider the lateral-directional problem and the other half will consider the longitudinal-direction problem. You are to decide amongst yourselves who will work on each problem. A separate report is to be submitted for the longitudinal and lateral components and they will be marked independent of one another.*

Longitudinal System Report page limit: 30 pages

Objective: You are set the task of designing the control laws for the aircraft. The objective is to develop a vertical speed autopilot with auto-throttle that will make the aircraft track a specified vertical speed by using the elevator actuator while regulating airspeed with throttle. The nominal flight condition is the higher of your two airspeed conditions.

1. Determine $G_{\delta_e}^{v_s}$, and use root locus tools ('sisotool') to investigate why the design of an autopilot based on using elevator to directly control vertical speed is problematic (if designed to meet the same specifications as Question 3). Discuss the nature of the inherent problems.

2. Design a pitch rate autopilot which seeks to control the pitch rate q using the elevator. Aim to satisfy a command bandwidth ω_c (-3dB point) of about 2 to 10 rad/s (you may vary this range depending on your findings and depending on the airspeed, provided you can justify the variation). Design for a noise bandwidth of 20 rad/s. Pitch rate step responses should have a settling time (to within 2% of the final value) of around 3 s.

You may wish to investigate a number of options for $K(s)$ as part of the design process. The evolution of your design should be described (e.g. by demonstrating how results for the rest of the questions improve).

3. Design a vertical speed guidance loop that incorporates the pitch rate controller as an inner loop. The guidance loop should use a compensator in the forward leg of the loop to convert vertical speed error into a pitch rate command. As part of your design process, you should assess the following;

- The nature of the aircraft response to a commanded 500 ft/min vertical speed command step input. The vertical speed step response should be designed for a rise time of about 3 s and to settle within about 10 s (closed loop bandwidth of about .5 to 2 rad/s).
- The nature of the pitch rate responses
- The nature of the control (elevator) activity in response to the vertical speed command step input.
- The transfer function relations that express the sensitivity of the open and closed loop pitch rate and vertical speed responses to longitudinal (u_g) and vertical (w_g) gusts.
- The magnitudes of the open and closed loop pitch rate, vertical speed and elevator responses to each gust component using the gust models and PSD analyses from Assignment 2.
- Draw the complete loop topology and develop the closed loop system equations
- Finally, comment on the effectiveness of the control system.

4. Design an *auto-throttle* control system. This loop will convert airspeed error into a throttle command. The design procedure is similar to question 3. As part of your design process, you should consider and/or assess the following;

- Draw the complete MIMO loop topology, noting that the airspeed and vertical speed loops are cross-coupled, and develop the closed loop system equations.
- Ensure that you evaluate the plant dynamics taking the vertical speed system coupling into account. The compensator should be designed for this plant.
- Design the loop to the same specifications as Question 3.
- Quantify the primary control effects ($G_{u_{c_{CL}}}^{u}(s)$ and $G_{v_{s_{c_{CL}}}}^{v_s}(s)$) and (where appropriate) compare them to the design responses obtained with only the vertical speed control loop operating. (Why is the throttle now effective in making airspeed changes?)

- Quantify the cross-coupling effects ($G^{v_s}_{u_{c_{CL}}}(s)$ and $G^{u}_{v_{s_{c_{CL}}}}(s)$) and (where appropriate) compare them to the responses obtained with only the vertical speed control loop operating.
- Assess the nature of the elevator and throttle activity in response to a vertical speed command step input and an airspeed command step input.
- Analyse the gust responses using the gust models and compare the responses to those with only the vertical speed loop in operation.
- Assess the effectiveness of the auto-throttle in managing the airspeed when the vertical speed controller is inactive (with and without the pitch rate controller operating).
- Finally, comment on the effectiveness of the control system.

For your final Design ...

5. Implement the control and guidance laws in the 6DOF nonlinear simulation by representing your controllers as a state space system. Verify that the theoretical responses are realisable in the time domain by generating time history plots and comparing them to relevant theoretical responses from the previous questions. What differences do you notice in the total aircraft response? (this question, being the practical outcome of the design, is worth <u>a lot</u>)

6. Simulate the gust effects in the time domain and numerically assess the effectiveness of the closed loop in rejecting gusts? Do these results agree with those obtained statistically in Questions 3 and 4?

7. Discuss what would happen if a large vertical speed was commanded? How could this be dealt with when implementing the control system? Demonstrate your approach in the nonlinear simulation. (What additional implications exist for the auto-throttle loop)

8. Analyse how the effectiveness of your control system changes if the aircraft is flown at the slower (off-design) flight condition in the same wind conditions (i.e. assess the *robustness* of the control system). What issues are involved? Perform the same analysis for the secondary *cg* condition.

Lateral-directional System Report page limit: 30 pages

Objective: You are set the task of designing the control laws for the aircraft. The objective is to develop a heading-hold autopilot that will make the aircraft seek and track a specified heading (*Yaw angle*) by using the aileron actuator. The nominal flight condition is the higher of your two airspeed conditions.

1. Determine $G^{\psi}_{\delta_a}$, and use root locus tools ('sisotool') to investigate why an autopilot based on using aileron to directly control heading is problematic (if designed to the same specifications as Question 3). Discuss the nature of the inherent problems.

2. Design a bank angle autopilot (wing-leveller) which seeks to control bank angle using aileron. You can expect to require a crossover frequency (command bandwidth (-3dB point)) in the region of 2 to 10 rad/s (you may vary this range depending on your findings and depending on the airspeed). Design for a noise bandwidth of 20 rad/s. Bank angle step responses should have a settling time of around 3 s. Steady-state error should be less than 1%. Ensure that your closed loop system does not command control inputs in excess of $\pm 20°$ in response to a $30°$ bank angle step input.

You may wish to investigate a number of options for $K(s)$ as part of the design process. The evolution of your design should be described (e.g. by demonstrating how results for the rest of the questions improve) .

3. Design a heading hold guidance loop that incorporates the wing-levelling autopilot. The guidance loop should use a compensator in the forward leg of the loop to convert heading (*Yaw angle*) error ($\Delta\Psi$) into a bank angle command (ϕ_c). As part of your design process, you should assess and consider the following;

- The nature of the aircraft response to a commanded 30 degree heading change (step input). The heading step response should be designed to settle within 10 s,
- The nature of the bank angle responses,
- The nature of the aileron control activity in response to the heading command step input.
- The nature of the bank angle and heading angle responses to gusts. Use the gust models and PSD analyses from Assignment 2 to compare the magnitudes of the open and closed loop bank angle, heading angle and aileron responses to each gust component.
- Illustrate the loop topologies where appropriate and develop the relevant closed loop system equations
- Comment on the effectiveness of the control system.

4. Design a classical yaw damper $\delta_r = K\frac{s}{s+a}r$ to improve the Dutch Roll dynamics.

- Draw the complete MIMO loop topology, noting that the bank angle control and yaw damper loops are cross-coupled, and develop the closed loop system equations.
- Re-evaluate the plant dynamics taking the yaw damper system into account. The bank angle compensator should be re-designed for this plant.
- Reassess the viability of designing a heading angle controller directly with aileron as in Question 1 (with yaw damper) and via the method of Questions 2 and 3 (with yaw damper).
- Re-design the bank angle control and heading loops to the same specifications as in Questions 2 and 3.

- Quantify the primary control effects ($G^{\phi}_{\phi_{c_{CL}}}(s)$ and $G^{\psi}_{\psi_{c_{CL}}}(s)$) and compare them to the design responses obtained without the yaw damper loop operating.

- Quantify the cross-coupling effects $G^{r}_{\phi_{c_{CL}}}(s)$) and $G^{r}_{\psi_{c_{CL}}}(s)$) and compare them to the design responses obtained without the yaw damper loop operating.

- Analyse the gust responses using the gust models and compare the responses to those without the yaw damper in operation.

- Assess the nature of the aileron and rudder activity in response to a bank angle command step input, a heading angle command step input, and the gust inputs.

- Discuss the relative merits of the three solutions (Q2 and 3, Q1 with yaw damper, Q2 and 3 with yaw damper) and their methods. Reinforce your arguments with similar robustness and gust rejection analyses and demonstrate the effectiveness of the solutions in the time domain ... as follows.

For your final Design ...

5. Implement the control and guidance laws in the 6DOF nonlinear simulation by representing your controllers as a state space system. Verify that the theoretical responses are realisable in the time domain by generating time history plots and comparing them to relevant theoretical responses from the previous questions. What differences do you notice in the total aircraft response? (this question, being the practical outcome of the design, is worth a lot)

6. Simulate the gust effects in the time domain and numerically assess the effectiveness of the closed loop in rejecting gusts? Compare these results with those obtained statistically in Question 3?

7. Discuss what would happen if a large heading change commanded? How could this be dealt with when implementing the control system? Demonstrate your approach in the nonlinear simulation.

8. Analyse how the effectiveness of your control system changes if the aircraft is flown at the slower (off-design) flight condition in the same wind conditions (i.e. assess the *robustness* of the control system). What issues are involved? Perform the same analysis for the secondary *cg* condition.