Chapter 10

1. What are flying and handling qualities requirements?

In the context of flying and handling qualities requirements explain the following,

- Flight envelope.
- Aircraft class.
- Flight phase category.
- Level of flying quality.
- The Cooper-Harper rating scale.

The pitch rate response to elevator control transfer function for the Northrop F-5 Tiger aircraft in level flight cruise at an altitude of 30,000 ft is given by,

\[
\frac{q(s)}{\eta(s)} = \frac{-14.6s(s + 0.0159)(s + 0.474)}{(s^2 + 1.027s + 7.95)(s^2 + 0.0169s + 0.0031)} \frac{1}{s}
\]  

(S10.1)

Evaluate the flying qualities of the aircraft at this flight condition. Note that \( n_\alpha = 12.9 \) 1/rad for this flight condition.

With the aid of MATLAB or Program CC, draw a root locus plot to show the effect of pitch rate feedback to elevator and show both modes clearly. Draw the flying qualities limit boundaries on the plot and hence determine a suitable value for the feedback gain \( k_q \) to ensure the aircraft meets the requirements. Compare the characteristics of the stability modes at this gain with those of the unaugmented aircraft.

**Answer**

Flying and handling qualities requirements specify the minimum acceptable standard of aircraft flying and handling qualities. These are specified in documents issued by the relevant regulatory authority and compliance with these requirements must be demonstrated for each aircraft. The specifications also define the rules to which stability, control and handling of an aircraft must be defined and evaluated.

*Flight envelope:* Defines the operating boundaries of the aircraft in terms of altitude, Mach number and normal load factor.

*Aircraft class:* Aircraft types are classified broadly according to size and weight,

- Class I - Small, light aircraft
- Class II - Medium weight, low to medium manoeuvrability aircraft
- Class III – Large, heavy, low to manoeuvrability aircraft
- Class IV – High manoeuvrability aircraft

*Flight phase category:* Missions may be described as a succession of flight phases. These can be grouped into categories comprising a variety of tasks requiring similar flying qualities for their successful execution.

- Category A – Non-terminal flight phases that require rapid maneuvring, precision tracking, or precise flight path control.
Category B - Non-terminal flight phases that require gradual manoeuvring, less precise tracking and accurate flight path control.

Category C - Terminal flight phases that require gradual manoeuvring, precision flight path control

*Level of flying quality:* quantifies the degree of acceptability of an aircraft in terms of its ability to complete the mission for which it is designed. They indicate the severity of the pilot workload in the execution of a mission flight phase.

Level 1 – Flying qualities clearly adequate for mission flight phase.

Level 2 – Flying qualities adequate to accomplish the mission flight phase, but with an increase in pilot workload and, or, degradation in mission effectiveness.

Level 3 – Degraded flying qualities, but such that the aircraft can be controlled, inadequate mission effectiveness and high, or limiting, pilot workload.

*The Cooper-Harper rating scale:* used to assess the flying qualities, or more specifically the handling qualities, of an aeroplane in a given flight phase. The procedure for conducting the flight test evaluation and the method for post flight reduction and interpretation of pilot comments are defined. The result of the assessment is a pilot rating between 1 and 10. A rating of 1 suggests excellent handling qualities and low pilot workload whereas a rating of 10 suggests an aircraft with many handling qualities deficiencies. The adoption of a common procedure for rating handling qualities enables pilots to clearly state their assessment without ambiguity or the use of misleading terminology. A summary of the Cooper-Harper handling qualities rating scale is shown in Table S10.1.

<table>
<thead>
<tr>
<th>Adequacy for selected task</th>
<th>Aircraft characteristic</th>
<th>Demands on pilot (workload)</th>
<th>Pilot rating</th>
</tr>
</thead>
<tbody>
<tr>
<td>Satisfactory</td>
<td>Excellent</td>
<td>Very low</td>
<td>1</td>
</tr>
<tr>
<td>Satisfactory</td>
<td>Good</td>
<td>Low</td>
<td>2</td>
</tr>
<tr>
<td>Satisfactory</td>
<td>Fair</td>
<td>Minimal pilot compensation required</td>
<td>3</td>
</tr>
<tr>
<td>Unsatisfactory - warrants improvements</td>
<td>Minor deficiencies</td>
<td>Moderate pilot compensation required</td>
<td>4</td>
</tr>
<tr>
<td>Unsatisfactory - warrants improvements</td>
<td>Moderate deficiencies</td>
<td>Considerable pilot compensation required</td>
<td>5</td>
</tr>
<tr>
<td>Unsatisfactory - warrants improvements</td>
<td>Tolerable deficiencies</td>
<td>Extensive pilot compensation required</td>
<td>6</td>
</tr>
<tr>
<td>Unacceptable - requires improvements</td>
<td>Major deficiencies</td>
<td>Adequate performance not attainable</td>
<td>7</td>
</tr>
<tr>
<td>Unacceptable - requires improvements</td>
<td>Major deficiencies</td>
<td>Considerable pilot compensation required for control</td>
<td>8</td>
</tr>
<tr>
<td>Unacceptable - requires improvements</td>
<td>Major deficiencies</td>
<td>Intense pilot compensation required for control</td>
<td>9</td>
</tr>
<tr>
<td>Catastrophic - improvement mandatory</td>
<td>Major deficiencies</td>
<td>Loss of control likely</td>
<td>10</td>
</tr>
</tbody>
</table>

Table S10.1 – The Cooper-Harper rating scale
For the given Northrop F-5 Tiger example, cruise is defined as a Category B flight phase. From equation (S10.1), the longitudinal mode characteristics are as follows,

**Short period**: \( \zeta_s = 0.182, \ \omega_s = 2.820 \text{rad.s}^{-1} \)

**Phugoid**: \( \zeta_p = 0.152, \ \omega_p = 0.056 \text{rad.s}^{-1} \)

Table S10.2 below shows the short period damping requirements. Therefore, it can be seen that the aircraft’s short period damping only meets Level 3.

![Table S10.2 – Short period mode damping requirements](image)

The short period natural frequency requirements are usually displayed on plots of \( \omega_s \) against normal load factor per unit angle of attack \( n_\alpha \) and, from that for Category B flight, the aircraft’s natural frequency meets Level 1 requirements.

For the phugoid, the damping requirements are given in Table S10.3, from which it can be seen that the Level 1 requirement is met.

![Table S10.3 – Phugoid mode damping requirements](image)

The requirement for phugoid natural frequency is,

\[
\frac{\omega_p}{\omega_s} \geq 0.1 \quad (S10.2)
\]

For this example, \( \omega_p / \omega_s = 0.02 \), hence the above requirement is met.

Overall, due to the low short period damping, the aircraft handling qualities are Level 3, hence some form of stability augmentation is required.

The effect of pitch rate feedback on the short period and phugoid modes are shown in Figure S10.1 and S10.2 respectively. The Level 1 flying quality boundaries for Category B flight phase are also shown on the root locus plots.
From the root locus plot analysis, the aircraft will first meet Level 1 flying qualities i.e. $\zeta > 0.3$ when $k_q = -0.05$. However, allowing for a reasonable margin of error and uncertainty, a practical choice might be $k_q = -0.22$. With this feedback gain, the closed-loop, longitudinal mode characteristics are as follows,
Short period: $\zeta_s = 0.689, \omega_s = 3.077 \text{rad.s}^{-1}$

Phugoid: $\zeta_p = 0.156, \omega_p = 0.051 \text{rad.s}^{-1}$

2. Describe the service and operational flight envelope for an aircraft and explain how they are related.

In the context of flying and handling qualities, what is meant by flight phase category? Why are the stability requirements associated with each flight phase category different?

Answer

The service flight envelope defines the boundaries of altitude, Mach number and normal load factor which encompass all operational mission requirements. The operational flight envelope defines the boundaries of altitude, Mach number and normal load factor for each flight phase. The operational flight envelopes therefore lie within the service flight envelope.

Flight phases are grouped into three categories, with each comprising a variety of tasks requiring similar flying qualities for their successful execution. The stability requirements associated with each flight phase category differ as each requires varying levels of manoeuvrability, precision tracking and flight path control.

3. The Lockheed Jetstar is a small four engined utility transport aircraft. When cruising at Mach 0.5 at an altitude of 40,000 ft, the roll and yaw transfer functions are given by,

\[
N_\phi(s) = -0.929(s - 0.0133)(s^2 + 0.133s + 0.79)1/s
\]

\[
N_\zeta(s) = -0.511(s + 0.36)(s + 0.098)(s + 0.579)1/s
\]

\[
\Delta(s) = (s - 0.0008)(s + 0.576)(s^2 + 0.009s + 1.26)
\]

Evaluate the stability modes characteristics at this flight condition against the flying qualities requirements.

What negative feedback is required to improve the stability characteristics of this aircraft? Illustrate your answer with a sketch of the appropriate root locus plot(s) and state the most significant effects of the feedback with reference to the requirements.

Answer

For flying qualities analysis, cruise flight is classed as a Category B flight phase and the aircraft’s stability mode characteristics are obtained as follows,

Roll subsidence mode: Time constant $T_r = 1.736s$. As this is greater than 1.4s but less than 3.0s, the aircraft’s roll mode meets Level 2 requirements.

Spiral mode: Time constant $T_s = 1250s$. The time to double bank angle is found from,

\[T_2 = T_s \ln 2 = 866s\]
As this is greater than 20s, the spiral mode meets Level 1 requirements.

**Dutch Roll**: \( \zeta_d = 0.0040, \ \omega_d = 1.122\text{rad.s}^{-1}, \ \zeta_d\omega_d = 0.0045 \)

In terms of damping ratio and the product of damping ratio and natural frequency, the aircraft’s dutch roll mode only meet Level 3 requirements.

To improve the roll mode characteristics to meet Level 1 requirements, roll rate feedback should be applied to the ailerons, the effects of which are shown in Figure S10.3. This describes the classical roll damper and negative roll rate feedback to the ailerons is equivalent to an increase in the roll damping properties of the wing. The spiral mode and dutch roll modes will be largely unaffected by this type of feedback.

![Figure S10.3 – Effect of roll rate feedback to ailerons](image)

The dutch roll characteristics can be improved by feeding back yaw rate to the rudder, shown in Figure S10.4. This describes the classical yaw damper and as the gain is increased, the dutch roll damping will increase rapidly, while the frequency remains almost constant. At the same time, yaw rate feedback to the rudder will also increase the stability of the spiral mode. The roll mode is almost completely unaffected by this form of feedback.
4. Explain why the characteristics of the short term stability modes are critical to good flying qualities.

**Answer**

The short term stability modes (short period, roll subsidence and dutch roll modes) are critical to good flying qualities as their time constants and natural frequencies are similar to those of the human pilot.

To avoid man-machine interaction of an unfavourable kind, these modes must be stable and reasonably well damped. Deficient short term modes will lead to difficult or dangerous flying qualities.

**Figure S10.4 – Effect of yaw rate feedback to rudder**