Mech 6091 – Flight Control System Course Project

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Outline

1. Linearization of Nonlinear F-16 Model
2. Longitudinal SAS and Autopilot Design
3. Lateral SAS and Autopilot Design
4. Nonlinear Simulation
5. Conclusion
Linearization of Nonlinear F-16 Model

Selection of trim condition:

Altitude = 10000 m
Speed = 300 m/s

By running ‘runF16model.m’, the inputs and states of trimmed condition can be calculated.
## Linearization of Nonlinear F-16 Model

<table>
<thead>
<tr>
<th></th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$h$ (Altitude)</td>
<td>10000 m</td>
</tr>
<tr>
<td>$V_T$ (True Air Speed)</td>
<td>300 m/s</td>
</tr>
<tr>
<td>$\alpha$ (Angle of Attack)</td>
<td>2.9915 deg</td>
</tr>
<tr>
<td>$\theta$ (pitch angle)</td>
<td>2.9915 deg</td>
</tr>
<tr>
<td>$\delta_{th}$ (thrust input)</td>
<td>0.32232</td>
</tr>
<tr>
<td>$\delta_e$ (elevator input)</td>
<td>-2.1068 deg</td>
</tr>
<tr>
<td>$pow$ (power)</td>
<td>20.9313%</td>
</tr>
</tbody>
</table>
Linearization of Nonlinear F-16 Model

The system include:
1. Nonlinear aircraft model
2. Actuators

Linearization of Nonlinear F-16 Model

- For longitudinal motion, the states include:

\[
[V_T \ a \ \theta \ q \ h \ X]
\]

- For lateral motion, the states include:

\[
[\beta \ \phi \ p \ r]
\]
Longitudinal Controllers Design

Control Diagram
Longitudinal Controllers Design

Open-loop System:

\[
\frac{\theta}{\delta_e} = \frac{-177.1944(s + 0.4158)(s + 0.0023)(s + 0.0072)}{(s + 0.5148 \pm j1.4176))(s - 0.0633)(s + 0.0591)(s + 0.0018)}
\]

SAS System:
Longitudinal Controllers Design

Flying Quality Requirements (MIL-8785C):
1. Category B is applicable for cruise
2. In general, Level 1 flying qualities should be compliant throughout the operational flight envelope
Longitudinal Controllers Design

**Flying Quality Requirements:**

- The first item is that the aircraft should be longitudinal stable;
- The long-period damping should be at least zero ($\zeta_{ph} \geq 0$).
- Short-period frequency should be put at a reasonable value according to requirement. This value is selected based on another value of $n_\alpha$, which is the gradient of load factor with respect to angle of attack. This value is related to the short-period time constant $T_{\theta_2}$. This time constant can be approximated by checking the zero of elevator-to-pitch rate transfer function, which is found to be 0.42 in the case. By using the equation of $T_{\theta_2} = V_T / g * n_\alpha$ [3], The value of $n_\alpha$ can be calculated and its value is 72.89. Then according to the requirement, the allowable range of natural frequency is estimated to be between 2.85 $rad/s$ to 10.6 $rad/s$.
- The short-period damping ratio should be within the range of 0.30 and
Longitudinal Controllers Design

Root-locus with $\alpha$ feedback:
Longitudinal Controllers Design

Root-locus with $q$ feedback:

$$k_q = -0.32$$

$$s = 2.2116 \pm j2.1282$$

with the natural frequency of 3.0693, and damping ratio of 0.72
Longitudinal Controllers Design

Pitch-Attitude Hold Autopilot: Proportional-Integral Controller

Controller Parameters are:

\[ K_p = 1.6, \ K_i = 1.8 \]
Longitudinal Controllers Design

Pitch-Attitude Hold Autopilot Response with 5 degree input:
Longitudinal Controllers Design

Stability Margin:

Bode Diagram
Gm = 8.29 dB (at 7.42 rad/sec), Pm = 31.5 deg (at 5.46 rad/sec)
Longitudinal Controllers Design

Speed-Hold Autopilot:
PI Controller with Parameters of
\[ K_p = 0.13, \quad K_i = 0.0028 \]

Altitude-Hold Autopilot:
PI Controller with Parameters of
\[ K_p = 0.0005 \text{ and } K_i = 0.00001 \]
Longitudinal Controllers Design

Altitude-Hold Autopilot Response with 200m Step Input:
Longitudinal Controllers Design

Speed-Hold Autopilot Response:

Time Series Plot:
Lateral Controllers Design

Control Diagram

Roll Angle Command

Integrator → Control Gain → Actuator → Aircraft

States Feedback

Roll Angle
Lateral Controllers Design

LQR Controller is selected but a new state of integrated error is introduced (given in $\epsilon$, where $\dot{\epsilon} = r - y$), and the controller becomes LQI type (Linear Quadratic Integral).

It should also be noted that because the controller is designed based on the linear model, the roll angle should be operated inside the linear region, which is generally within the range of $\pm 5.0$. 
Lateral Controllers Design

Lateral Flying Quality Requirements:

- Dutch roll damping ratio $\zeta_d \geq 0.08$, natural frequency $\omega_{nd} \geq 0.4 \text{ rad/s}$, and finally $\zeta_d \omega_{nd} \geq 0.15 \text{ rad/s}$.

- Roll mode time constant $\tau_r \leq 3 \text{ s}$.
Lateral Controllers Design

$Q$ and $R$ matrices:

$$Q = \begin{bmatrix} 200 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 10 \end{bmatrix}$$

$$R = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}$$
Lateral Controllers Design

Feedback Gains:

\[
K = \begin{bmatrix}
1.4629 & -1.8854 & -0.3243 & -0.4551 & 0.4533 & -0.0204 & 3.155 \\
10.2559 & 0.1806 & 0.1486 & -2.9086 & -0.0204 & 0.4119 & -0.215
\end{bmatrix}
\]

The ducth-roll poles :

\[
s = -3.7016 \pm j4.2973
\]

The roll time constant:

0.3262
Lateral Controllers Design

Roll Angle Response:

![Graph showing the roll angle response over time](image-url)
Lateral Controllers Design

Observer Structure:

- Actuator
- Aircraft
- Observer
  - Gain
  - Estimated Roll Angle
- Aircraft Roll Angle
- Estimated Aircraft States
Observer Poles and Feedback Gains:
the poles of observer are placed at $[-4 \quad -4 \quad -4 \quad -4]$, and the feedback gains are:

$$H = [-3.2703 \quad 141056 \quad 60.1786 \quad -15.0705]^T$$
Lateral Controllers Design

Observer Response:

- Side Slip Angle (deg)
- Yaw Rate (deg/sec)
- Aileron Input (deg)
Lateral Controllers Design

Observer Based LQI Controller Response
Nonlinear Simulation

Longitudinal Simulation
Nonlinear Simulation

Lateral Simulation: Roll Angle Response
Nonlinear Simulation

Lateral Simulation: Trajectory

![3D plot of trajectory]
Nonlinear Simulation

Lateral Simulation: Observer Response
Conclusion

1. The longitudinal SAS and autopilots have been designed based on the linear model using classical control techniques. Each channel has to be tuned to achieve a good response.

2. An observer based LQI controller is designed based on linear model using modern control techniques. The observer and controller show good responses.

3. In nonlinear simulation, the controller performance deteriorated because of coupled components and nonlinearities. However, because of the integral parts of the controllers, the system can still track the commands without steady-state error.