Maneuverability analysis on flying vehicle with thrust vectoring system

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Abstract. Fighter aircraft often require unconventional maneuverability that civil aircraft cannot perform. The conventional flight control devices are not sufficient for this maneuver. Thus, to be able to perform unconventional maneuvers, additional control devices may be required, such as the thrust vectoring system (TVS). This paper will discuss the effect of TVS implementation in improving maneuverability. In this work, a dynamic model of F-4 Phantom is used as the basis for the study. The dynamic model of the aircraft with TVS is constructed analytically and numerically. The nonlinear model obtained from the modeling process then linearized at a particular flight condition and some TVS deflection values. Further, the linear system and control approach is employed for evaluating and designing the linear controllers for stabilization and maneuvering tasks. The closed-loop system, which is implemented in the MATLAB/Simulink environment, then numerically simulated and observed for analyzing the effect of implementing different TVS deflection on the required control effort in high angle of attack maneuvers. The simulation results show that the TVS can affect the performance of the closed-loop system in stabilization tasks. While at some deflection values, TVS can also help to reduce the required control effort to tracking attitude reference command when executing the high angle of attack maneuvers.

Keywords: Thrust vectoring system, high angle of attack maneuver, flight control system, flight dynamics, aircraft modeling

1. Introduction
In carrying out its mission, fighter aircraft often require unconventional maneuverability that civilian aircraft cannot perform. With unconventional maneuvers, unconventional control devices are needed. The thrust vectoring system (TVS) is an example of unconventional control devices, which direct the thrust of the jet engine in the desired direction to control the aircraft's attitude.

In this research, the use of TVS is expected to increase the maneuverability of the fighter aircraft. This research will present and analyze how using TVS can help the aircraft to achieve a high angle of attack maneuver. The scopes of the research are the aircraft model used is the F-4 Phantom aircraft, the flight control system is developed using the linear approach, flights are simulated during high angle of attack maneuver, the dynamics of the control devices, including the TVS, are neglected or simplified, the control devices’ responses are instantaneous, TVS’ are assumed fixed in certain setting angles, not
as a control input, although the setting angles are varied, and motion is considered only in longitudinal mode.

2. Modeling of the Aircraft
The aircraft is modeled for four different thrust vectoring system deflections, $\delta_{TVS} = -5^\circ$, $0^\circ$, $5^\circ$, and $10^\circ$. The F-4 Phantom aircraft model is used, as presented on Fig. 1 and Table 1.

![Figure 1. F-4 Phantom Aircraft [1]](image)

| Table 1. F-4 Phantom Specifications [1-2] |
|------------------------------------------|
| Parameter                        | Value          | Unit      |
|---------------------------------|----------------|-----------|
| Mass (m)                        | 17656          | kg        |
| Inertia X; Y; Z ($I_X; I_Y; I_Z$) | 33855; 165667; 189543 | kg.m$^2$ |
| Inertia ZX ($I_{XZ}$)           | 1593           | kg.m$^2$  |
| Length                          | 19.2           | m         |
| Height                          | 5              | m         |
| Mean Aerodynamic Chord (c̅)     | 4.3            | m         |
| Center of Gravity Reference (CGref) | 0.298 $c^\bar{}$ | -      |
| Engine to CG (X_B-axis) Distance | 6              | m         |
| Engine to CG (Z_B-axis) Distance | 0.0005         | m         |
| Power Plant: 2 x General Electric J79-GE-17A after-burning turbojet | 79.38 | kN |

The basic equations of motion on the body reference frame, in the time domain, considering only longitudinal motions are presented in equations 1 to 3 [1,3-4]:

$$-W \sin \theta + \bar{q}SC_X + T = m(\ddot{u} + qw - rv)$$

$$W \cos \theta \cos \phi + \bar{q}SC_x = m(\dot{w} + pv - qu)$$

$$\bar{q}SC_m = I_y \ddot{q} + (I_x - I_z)r \dot{p} + I_{xz}(p^2 - r^2)$$
The thrust component is separated from the aerodynamic coefficient. This component will have the effect of adding TVS.

Figure 2. Aircraft’s Simplified Free-Body Diagrams (FBD)

Figure 3. Aircraft’s Simplified Free-Body Diagrams (FBD) with TVS

By reviewing Figures 2 and 3, Equations 1, 2, and 3 will be modified due to TVS addition.

\[ -W \sin \theta + \dot{q} S C_x + T \cos \delta_{TV C} = m(\dot{u} + qw - rv) \] (4)

\[ W \cos \theta \cos \phi + \dot{q} S C_z - T \sin \delta_{TV C} = m(\dot{w} + pv - qu) \] (5)

\[ \ddot{q} S C_m + T \sin \delta_{TV C} \cdot x_T + T \cos \delta_{TV C} \cdot z_T = I_y \dot{\phi} + (I_x - I_z) \rho + J_{xz} (p^2 - r^2) \] (6)

A positive deflection of $\delta_{TVS}$ means TVS is deflected downward. This deflection will produce thrust force in Z-axis upward. It will help the tail to move upward and the aircraft to pitch down. The non-dimensional aerodynamic force and moment coefficients already covered flight conditions on the high angle of attack maneuvers.

The $15^\circ < \alpha \leq 30^\circ$ coefficients are used in the model. These coefficients represent the trimmed condition at $\alpha = 30^\circ$. Small changes in $\alpha$ values are covered in the same coefficients. They are computed as follows [1].

\[ C_X = 0.141 - 0.0154 \alpha + 2.96 \times 10^{-4} \alpha^2 + 1.82 \times 10^{-3} \delta_e - 7.3 \times 10^{-5} \delta_e \alpha \]
\[ + \left( \frac{180qC}{\pi 2V} \right) (-0.0602 + 2.04 \times 10^{-3} \alpha) \] (7)

\[ C_Z = -0.608 - 0.0222 \alpha - 6.77 \times 10^{-3} \delta_e + 9.7 \times 10^{-5} \delta_e \alpha \]
\[ + \left( \frac{180qC}{\pi 2V} \right) (1.136 - 0.1418 \alpha + 3.1 \times 10^{-3} \alpha^2) \] (8)

\[ C_m = 0.0549 - 6.08 \times 10^{-3} \alpha - 8.14 \times 10^{-3} \delta_e + 1.1 \times 10^{-4} \delta_e \alpha \]
\[ + \left( \frac{180qC}{\pi 2V} \right) (-0.0951 + 1.4 \times 10^{-3} \alpha) + (x_{c.g.\_ref} - x_{c.g.}) C_Z \] (9)

The numerical modeling is done with help of MATLAB and Simulink device. In constructing the equations of motion, the 6DOF Quaternion block is used compared to Euler to avoid singularity due to a 90 degree of pitch angle.
The parameters used in the Quaternion block are 8000 m altitude with initial velocities $u = 55$ m/s and $w = 31.7543$ m/s so that $\alpha$ becomes $30^\circ$. Initial Euler angles and body rotation rates are set as zero.

The aerodynamic and the control surfaces components are included in the Aerodynamic Forces and Moments block. The gravity and thrust components are independent of the aerodynamic coefficients, also not included in the calculations in the 6DOF Quaternion block, so these components are modeled in separate subsystems.

3. Controller Design

To design a controller, the nonlinear aircraft models are trimmed and linearized with the Linear Analysis Tool by Simulink Control Design. After the trimming process is completed, an operating point has been created. Trim values of inputs and outputs are gained and system characteristics are checked.

The systems with $\delta_{TVS} = -5^\circ$ and $0^\circ$ are considered as stable systems. While the systems with $\delta_{TVS} = 5^\circ$ and $10^\circ$ are otherwise. They need stabilization with the Linear Quadratic Regulator (LQR) control method. Apart from stability issues, the damping ratio of the system have to meet Military Specification: Flying Qualities of Piloted Airplanes by U.S. Military (MIL-F-8785C). [6] The high angle of attack maneuver is classified as a Class IV airplane with Category A. To achieve Level 1 of the short-period response, the damping ratio shall be within the limits of 0.35 to 1.3.

Before the LQR control method is performed, the controllability and observability of the system need to be checked. The systems are considered as a fully controllable and observable system, so the LQR control can be performed. Tables 2 and 3 below show the poles and damping ratio, both for open-loop and closed-loop system (results of the LQR method).

**Table 2. LQR Results for $\delta_{TVS} = -5^\circ$ and $0^\circ$.**

| $\delta_{TVS} = -5^\circ$ | $\delta_{TVS} = 0^\circ$ |
|---------------------------|---------------------------|
| Poles (O.L; C.L) | $\zeta$ (O.L; C.L) | Poles (O.L; C.L) | $\zeta$ (O.L; C.L) |
| -4.57e-02; -6.51e-02 | 1; 1 | -5.9e-02; -7.95e-02 | 1; 1 |
| -6.16e-03+1.37e-01i; -9.77e-01 | 4.49e-02; | -3.58e-03+1.2e-01i; -1.33+1.11e+001 | 2.99e-02; 7.68e-01 |
| -6.16e-03-1.37e-01i; -3.21 | 4.49e-02; 1 | -3.58e-03-1.2e-01i; -1.33-1.11e+001 | 2.99e-02; 7.68e-01 |
| -1.07; -1.98e+01 | 1; 1 | -1.06; -2.01e+01 | 1; 1 |
Table 3. LQR Results for $\delta_{TVS} = 5^\circ$ and $10^\circ$

| $\delta_{TVS} = 5^\circ$ | $\delta_{TVS} = 10^\circ$ |
|---------------------------|---------------------------|
| Poles (O.L; C.L)          | $\zeta$ (O.L; C.L)        | Poles (O.L; C.L)          | $\zeta$ (O.L; C.L)        |
| -8.44e-02; -1.06e-01      | 1; 1                      | 1.82e-02+7.96e-02i; -1.52e-01 | -2.22e-01; 1 |
| 4.23e-03+9.96e-02i;       | -4.25e-02;                | 1.82e-02-7.96e-02i;        | -2.22e-01;               |
| -1.43+8.72e-01i           | 8.54e-01                  | -6.14e-01                  | 1                       |
| 4.23e-03-9.96e-02i;       | -4.25e-02;                | -1.24e-01;                 | 1                       |
| -1.43-8.72e-01i           | 8.54e-01                  | -3.98                      | 1                       |
| -1.05; -2e+01             | 1; 1                      | -1.04; -1.95e+01           | 1; 1                    |

Equations 10 to 13 show the gain results (K) from the LQR method.

\[
K_{\delta_{TVS} = 5^\circ} = \begin{bmatrix}
-0.9241 & -0.1246 & -49.4509 & -17.1285 \\
2.1053 & -0.5551 & 12.0508 & -7.1696
\end{bmatrix} \quad (10)
\]

\[
K_{\delta_{TVS} = 0} = \begin{bmatrix}
0.0219 & -0.0039 & -59.5057 & -31.9083 \\
2.2428 & -0.6196 & 37.9755 & -3.2288
\end{bmatrix} \quad (11)
\]

\[
K_{\delta_{TVS} = 5^\circ} = \begin{bmatrix}
2.0782 & -0.3928 & -2.4523 & -39.0860 \\
0.9072 & -0.4915 & 79.8256 & 22.3168
\end{bmatrix} \quad (12)
\]

\[
K_{\delta_{TVS} = 10^\circ} = \begin{bmatrix}
2.1280 & -0.5901 & 49.9387 & -20.7811 \\
-0.8449 & -0.1263 & 59.5931 & 28.8254
\end{bmatrix} \quad (13)
\]

4. Simulation and Analysis
The aircraft model is built with the tracking concept for $\alpha$ and $\gamma$ through $V$. Figure 5 shows its Simulink model. The reference values for both $\alpha$ and $\gamma$ are set. $\alpha$ is related to the elevator deflection input, while $\gamma$ affects the $V$ that is related to the throttle deflection input.

![Figure 5. Tracking Model [6]](image-url)
The state variables are being feed-backed by the gain K from the LQR control method. α, V, and γ, are being feed-backed with PID control. \( \alpha_{\text{ref}} \) is set as the signal in Figure 6 below, while \( \gamma_{\text{ref}} \) is set to a constant value of 0°.

![Figure 6. Reference Signal](image)

The PID Controllers are used for α and γ tracking. PID blocks in Simulink are used and automatically tuned for the tracking model. Figure 7 shows the outputs for tracking variables, Figure 8 shows other outputs from the model, while Figure 9 shows the control variables responses.

![Figure 7. Tracking Outputs](image)

![Figure 8. Other Outputs](image)
The α responses follow the reference signal. While the γ responses disturbed because it is difficult to keep the γ to 0° while the α keeps changing. The system needs a slower time for α changes because there is a time delay to adjust the γ. It also can be caused by limited control for thrust. For α, there is an elevator as a control input, that can be deflected upward and downward. For V, there is the thrust that is effective only for increasing the airspeed, but not decreasing it. Other control inputs for V, such as airbrake or spoiler is needed so the γ tracking can perform better.

In this case, as the δ\textsubscript{TVS} increases, the responses of u and θ quite similar. The responses of q increase. The responses of Xe similar, the aircraft keeps moving forward. The responses of h end in the lower values, but the response of δ\textsubscript{TVS} = 10° does not follow the path. It may be caused by the limits of aircraft performance.

For the control variables, as the δ\textsubscript{TVS} increases, the efforts of δ\textsubscript{e} are increase. It means that the model with δ\textsubscript{TVS} = -5° has the lowest effort for δ\textsubscript{e}, as it helps the aircraft pitching up. While the responses of δ\textsubscript{T} quite similar to greater value for greater δ\textsubscript{TVS}.

5. Conclusion

The dynamics of fighter aircraft using thrust vectoring system (TVS) as one of its control devices are successfully modeled. The flight control systems, involving the use of TVS, are also successfully designed. The closed-loop behaviors of the aircraft under the TVS implementation are simulated and analyzed. To analyze the effect of using TVS on fighter aircraft, the aircraft is modeled in four variations of δ\textsubscript{TVS}, which are -5°, 0°, 5°, and 10°. From Tables 2 and 3, it can be seen that the stability controllers are well performed and result in stable responses. From Figures 7 to 9, it can be seen that negative δ\textsubscript{TVS} helps the aircraft to pitch up, and vice versa. Greater δ\textsubscript{TVS} led to lower δ\textsubscript{e}. It can help the works of δ\textsubscript{e} by minimizing elevator efforts. It means that TVS can help the aircraft to do the high angle of attack maneuver. For the better results of the research, the TVS should be dynamically modeled in the aircraft dynamic model so that the results can be more realistic. TVS also can be used as the control input to the aircraft. The deflection can change by time in a certain flight condition.

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