29 Jan 1993

Analysis of a Thrust Vectoring Fighter Aircraft Using Realtime Flight Simulation

Clinton A. Thessen

Recommended Citation

Thessen, Clinton A., "Analysis of a Thrust Vectoring Fighter Aircraft Using Realtime Flight Simulation" (1993). *Opportunities for Undergraduate Research Experience Program (OURE)*. 110.
https://scholarsmine.mst.edu/oure/110

ANALYSIS OF A THRUST VECTORING FIGHTER AIRCRAFT USING REAL-TIME FLIGHT SIMULATION

Clinton A. Thessen

Department of Mechanical and Aerospace Engineering and Engineering Mechanics

ABSTRACT

A real-time flight simulation model based on the McDonnell Douglas F/A-18 Hornet was created. This model was then modified with two different styles of thrust vectoring so that a study of each system's effect on the aircraft's pitch performance could be conducted in order to determine the best system. At present, work is proceeding on the development of active flight controls for the aircraft. After that effort is completed the thrust vectoring study can begin.

INTRODUCTION

As the military budget declines and the air-to-air capabilities of foreign nations grow, the U.S. struggles to field an aircraft that is operationally superior and inexpensive compared to other nations' aircraft. The Defense Department therefore seeks to maintain this superiority by upgrading existing aircraft. This allows them to stretch out new aircraft programs while maintaining the competitive edge in air combat that the U.S. has enjoyed over the past 20 years, and at the same time lessen the financial burden that new aircraft programs pose to a tight defense budget.

One way to accomplish this goal is to refit existing aircraft with thrust vectoring nozzles. Thrust vectoring expands the aircraft's maneuvering envelope and allows the aircraft to maneuver more quickly than normal. Thrust vectoring is the process of deflecting the aircraft's thrust directionally to produce changes in aircraft pitch, roll and yaw. By using thrust vectoring, a control surface's required deflection for a given control stick input can be lessened due to the change in moments that the thrust vectoring produces. For example, for a given pitch maneuver, an F/A-18's stabilators have to produce some pitching moment. If thrust vectoring produces a portion of that required moment, then the stabilators are free to add to the pitching moment. This allows the aircraft to perform the maneuver more quickly, or use that remaining control power to add to roll performance.

Currently, there are four basic types of thrust vectoring systems. One type is the two-dimesional wedge system that has been tested on the McDonnell Douglas F-15 S/MTD (STOL/ Maneuvering Technology Demonstrator) and has also found its way onto the Lockheed F-22. Another is a three paddle system for three-dimensional vectoring used on the NASA/McDonnell Douglas F/A-18 HARV (High Angle of attack Research Vehicle). A third is a rotating paddle/vane system mounted on a rotating circle housing which allows for three-dimensional vectoring to be used on the X-31. Finally, an actual nozzle system is used on the McDonnell Douglas AV-8B Harrier. This system rotates in one plane, which only allows two-dimensional vectoring. Only the two-dimensional wedge and the three-paddle configurations will be considered in this study.

The objective of this research is to determine which of the two systems modelled produces the greatest increase in aircraft pitch plane performance using two-dimensional thrust vectoring.

FORMULATION

Aircraft Model Development

The first step in performing any aircraft research is to determine which aircraft to use. For this thrust vectoring study, it was determined to use the McDonnell Douglas F/A-18 Hornet because it represents the low end, with regard to cost, of a high-low aircraft mix in the Naval Aviation inventory. However, that does not represent the aircraft's capability. As an air-to-air combat and air-to-ground attack aircraft, there is no equal in the world. Because of this and the fact that NASA has already fitted a F/A-18 Hornet (HARV) with thrust vectoring, this aircraft seemed to be the logical choice.

Now, the next step was to find flight data that could be used to model the aircraft mathematically. After an extensive search, the only document found that contained useable data was Reference [1], however, this data was essentially in the incompressible flow regime. This data was processed and expanded into a form that could be used by the flight simulation code. This required curve-fitting the data between known data points and performing a compressiblitiy correction on the data using the Karman-Tsien rule up to airspeeds of Mach 0.8, Ref. [2]. The upper limit of Mach 0.8 was chosen due to the fact that an accurate approximation of transonic and supersonic aerodynamic performance would be impossible and that the majority of any air-to-air combat the F/A-18 participates in is usually performed at high subsonic velocities. Using this data, various stability coefficients were calculated using Refs. [3] and [4]. They are summarized in Table I.

After the required data was obtained, the current flight simulation code, Ref. [5], was modified in order to represent the F/A-18. All of the subroutines were changed to be compatible with the increased number of table lookups of the flight data. Also, the force and moment equations were modified to calculate the aircraft state using the increased amount of available flight data that pertained to the F/A-18. Since the model that was modified to simulate the F/A-18 was the Cessna 210 there were several flight control changes. For instance, the F/A-18 has an all-moving tail, a stabilator, while the Cessna 210 has the traditional stabilizer/elevator setup. In addition, the entire geometric layout was changed. Another area that had to be modified was the command menus used to setup the flight simulator initial conditions before the pilot can proceed to fly the aircraft.

Once the modification of the flight simulation code was completed I found that the aircraft was dynamically unstable, even though it would fly. It is difficult to fly straight and level, however, it is practically impossible to fly with any control stick input. When such a maneuver is attempted the aircraft diverges from the commanded flight path and spins out of control into the ground. Options to alleviate this problem were researched. The two options that were deemed worthy were to: 1) change the stability coefficients so that the aircraft would be dynamically stable, which meant changing the aircraft geometry, or 2) develop an active control system. Since I wanted the model to be a true representation of the real aircraft, I did not want to start altering surface areas and moment arms, so I decided to develop an active control system.

Aircraft Active Control System Development

The active control system used is a basic feedback control system. The aircraft monitors its attitude. If the aircraft pitch, roll and yaw rates exceed a predetermined tolerance, the active control system will activate and command control surface deflections that will bring the aircraft back to its steady state value. In order to retain maneuverability, the aircraft math model will monitor control stick inputs, and if a rate tolerance is exceeded due to a pilot commanded stick input, then the active control system is overridden. This system will be needed for all planes of aircraft motion, longitudinal (pitch plane) and lateral-directional (roll and yaw planes).

In order to develop this active control system and make it work with the flight simulator, gains had to be calculated and tabulated in the correct form so that the flight simulation code can perform table lookups on the gain data. Once the gains are determined they are multiplied by the corresponding control deflection variable to command a control surface deflection(s) in order to remain on the current flight path. Determining these gains is the difficult part. A program was written that calculates the dimensional stability coefficients that are used to determine the elements in the matrices used by the Bass-Gura formula, ref. [7], shown below;

$$[(([Mc][W])^{-1}]^{T}*[(([a]-[\hat{a}]))] = [g] \qquad (1)$$

and then solves the equation for the gain matrix. This equation is solved for a matrix of data points using mach, altitude and γ for longitudinal control and mach, altitude, ϕ, and β for lateral-directional control. [Mc] is computed from the following equation, Ref. [7],

$$[Mc] = [[B] \mid [A][B] \mid [A]^{2}[B] \mid [A]^{3}[B] \ldots] \qquad (2)$$

TABLE I. STABILITY COEFFICIENTS

COEFFICIENT	**VALUE**	**DESCRIPTION**
$C_{L\alpha}$	4.5388	Slope of lift coeff. vs AOA
$C_{L\delta e}$	1.6082	Slope of lift coeff. vs δ_e
C_{Lu}	$M^2/(1-M^2)*C_{L1}$	Slope of lift coeff. vs u
$C_{D\alpha}$	1.249	Slope of drag coeff. vs AOA
$C_{D\delta e}$	1.3574	Slope of drag coeff. vs δ_e
C_{Du}	$0.214*C_{L1}*C_{Lu}$	Slope of drag coeff. vs u
C_{m0}	0.0244	Pitch mom. coeff. at $\alpha = 0.0$
$C_{m\alpha}$	-0.011605	Slope of pitch mom. coeff. vs α
$C_{m\alpha dot}$	-3.9295	Slope of pitch mom. coeff. vs α_{dot}
$C_{m\delta e}$	0.006436	Slope of pitch mom. coeff. vs δ_e
C_{mu}	$-0.000018824*M_1$	Slope of pitch mom. coeff. vs u
C_{mq}	-3.4484	Slope of pitch mom. coeff. vs q
$C_{v\beta}$	-1.2687	Slope of side force coeff. vs β
C_{vp}	$0.2925*C_L + 0.033101$	Slope of side force coeff. vs p
C_{vr}	$0.143*C_L + 0.647$	Slope of side force coeff. vs r
$C_{v\delta a}$	0.0	Slope of side force coeff. vs δ_a
$C_{v\delta r}$	0.3844	Slope of side force coeff. vs δ_r
Cl_{β}	$-0.391731*C_L + 0.049103$	Slope of rolling mom. coeff. vs β
C_{lp}	-0.20202	Slope of rolling mom. coeff. vs p
C_{lr}	$1.00578*C_L + 0.08308$	Slope of rolling mom. coeff. vs r
$C_{l\delta a}$	0.25	Slope of rolling mom. coeff. vs δ_a
$C_{l\delta r}$	0.0665	Slope of rolling mom. coeff. vs δ_r
$C_{n\beta}$	0.18321	Slope of yawing mom. coeff. vs β
C_{np}	$0.00315*C_L{}^2*\tan\alpha + 0.663*C_L +$ $0.001713 + 0.0377475*\tan\alpha$	Slope of yawing mom. coeff. vs p
C_{nr}	$-(0.025*C_L{}^2 + 0.0326184)$	Slope of yawing mom. coeff. vs r
$C_{n\delta a}$	$-0.15*C_L$	Slope of yawing mom. coeff. vs δ_a
$C_{n\delta r}$	-0.10623	Slope of yawing mom. coeff. vs. δ_r

Thrust Vectoring Development

Once the aircraft is controllable, due to the active control system development, the aircraft will be modified for pitch plane thrust vectoring. This effort will be fairly simple compared to everything else that has been developed. It will entail altering the force and moment equations again, to model a varying thrust vector. Also, the flight controls and crew station subroutine will have to be altered so that the pilot can control the vectoring. The control of the vectoring may have to be slaved to the control stick so that pilot workload does not become a problem. This will require the pilot only to turn the thrust vectoring on or off and allow him to forget about controlling the thrust vector. After those modifications are completed, a flight data recorder can be invoked to track selected variables throughout a flight. This will produce data that can be plotted vs time, and from these plots the best performing thrust vectoring system can be determined.

STATUS

Completed Work

At this time, all of the flight data and code modification work needed to develop a flying F/A-18 Hornet flight simulation model is finished. The aircraft model is flying, however, it is uncontrollable except for a limited amount of maneuvers.

This control problem will be eliminated with the development of the active control system. This control system development is past the formulation stage. All of the information to develop it has been gathered.

Work in Progress

The active control system is currently in development. Several utility subroutines have been written to perform various matrix operations. I am in the process of putting this all together into a workable set of code that will calculate the gains at different initial and perturbed conditions. Approximately 75% of this effort is complete.

Future Work

After the gain calculation program is complete it will be run at the previously mentioned data points. This data will then be formatted into a data table that will be compatible with the flight simulation lookup routines. Once this has been validated and the aircraft is flyable, the thrust vectoring study can start.

The thrust vectoring study will be quite simple and quick. Some basic maneuvers can be created and flown with and without thrust vectoring and then all of this data can be plotted and compared so that a determination of each configuration's merits can be made.

CONCLUSION

The entire project has not been completed, however, work proceeds smoothly. This project turned out to be quite a bit more involved than what was expected. Initially, I only needed to do the thrust vectoring study, however, which aircraft would I use as the testbed? None of the existing aircraft could satisfy my needs. Therefore I had to develop a new aircraft model. Now the one project has turned into two; aircraft model development and the thrust vectoring study. After the aircraft was flying it was discovered that the aircraft was uncontrollable. This meant that I had to develop an active control system. Now the one project had turned into three; aircraft model development, active control system development and finally the thrust vectoring study. Work on this project will continue beyond the time that this report is turned in and will continue until the end of this semester.

NOMENCLATURE

Variable	**Description**
C_{L1}	Lift coeff. at a steady state flight condition
M	Mach number
M_1	Mach number at steady state flight condition
x-axis	Positive out the aircraft nose
y-axis	Positive out the right wingtip
z-axis	Positive out the bottom of the aircraft
roll	Rotation about x-axis
pitch	Rotation about y-axis
yaw	Rotation about z-axis
p	Angular velocity about the x-axis
q	Angular velocity about the y-axis
r	Angular velocity about the z-axis
u	Velocity in the x-direction
α	Angle of Attack -- angle between velocity vector and x-y plane
β	Yaw angle - angle between velocity vector and x-z plane
δ_e	Elevator (stabilator) deflection
δ_a	Aileron deflection
δ_r	Rudder deflection
γ	Flight path angle
a	Open loop poles
$\hat{a}$	Close loop poles
[A]	State variable matrix
[B]	Control variable matrix
[g]	Gain matrix
[Mc]	Controllability matrix - derived from the state transformation matrix
[W]	Upper diagonal matrix of open loop poles

ACKNOWLEDGMENTS

There are several people who have offered me help, advice and support throughout the duration of this project. First I would like to thank Prof. Bruce P. Selberg for being my advisor on this project and giving me help during the initial problem formulation. While I was searching for F/A-18 flight data, I had a lot of help from Ray Whipple at NASA-Langley in regards to Reference [1]. A big thanks to Dr. S. N. Balakrishnan for his help with the procedure to develop an aircraft active control system. Finally, I would like to thank my classmate and co-worker Holly Berendzen for her help with developing the code to calculate the gains that are used by the active control system integrated into the F/A-18 Hornet flight simulation model. Without her expertise in flight controls and due to my lack thereof, the active control system would have never been developed.

REFERENCES

(1) Hultberg, Randy. "Low Speed Rotary Aerodynamics of F-18 Configuration for 0° to 90° Angle of Attack - Test Results and Analysis." NASA Contractor Report 3608, Langley Research Center, 1984.

(2) Anderson, John D. Fundamentals of Aerodynamics. St. Louis: McGraw-Hill, Inc., 1991.

(3) McDonnell Douglas Corporation, Douglas Aircraft Division. "United States Air Force Stability and Control DATCOM." Long Beach, Ca., Douglas Aircraft Division, 1978.

(4) Smetana, Frederick O. "Computer Assisted Analysis of Aircraft Performance Stability and Control." McGraw-Hill, 1984.

(5) Sinnett, Kevin Michael. "The Development of a Real-Time Digital Flight Simulator on the Apollo DN10000VS." Thesis for MSAE at University of Missouri-Rolla. 1990.

(6) Roskam, Jan. Flight Dynamics of Rigid and Elastic Airplanes. Lawrence, Ka, 1972 by author.

(7) Friedland, Bernard. Control System Design - An Introduction to State-Space Methods. McGraw-Hill, 1986.

(8) Etkin, Bernard. Dynamics of Flight - Stability and Control. New York: John Wiley & Sons, 1958.