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FLIGHT DYNAMICS OF A VECTORED THRUST AIRCRAFT

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Abstract: **Nonlinear studies were made on the longitudinal motion of a vectored thrust aircraft. Rich dynamics was obtained with several bifurcations and even with chaos in the forced oscillation. The system has sensitivity to the pitching moment derivatives. The lateral motion was added to the system to get the full 6-degree-of-freedom motion. Three cases were separately investigated: the pure sideslip motion, the steady turn with no sideslip and the full motion. The aircraft that is presented by its mathematical model represented strong tendency to bank, but in other direction the motion was well damped. Chaos was observed in the autonom 6-degree-of-freedom system at high angle of attack replacing the wing rock. The simulation proved it is possible to do 180 degrees turn from level flight less than 8seconds.**

Nomenclature

b = reference span, m
c_D = drag coefficient, dimensionless
c = reference mean aerodynamic chord, m
c_L = lift coefficient, dimensionless
c_{L0} = static lift coefficient, dimensionless
c_{Lq} = lift derivative with respect to pitch rate
$c_{L\dot{\alpha}}$ = lift derivative with respect to $\dot{\alpha}$
c_l = rolling moment coefficient, dimensionless
$c_{l\beta}$ = rolling moment derivative with respect to sideslip angle, 1/rad
c_{lp} = roll damping derivative, 1/rad
c_{lr} = rolling moment derivative with respect to yaw rate, 1/rad
c_m = pitching moment coefficient, dimensionless
c_{m0} = static pitching moment coefficient, dimensionless
c_{mq} = pitching moment derivative with respect to pitch rate
$c_{m\dot{\alpha}}$ = pitching moment derivative with respect to $\dot{\alpha}$
c_n = yawing moment coefficient, dimensionless
$c_{n\beta}$ = yawing moment derivative with respect to sideslip angle, 1/rad
c_{np} = yawing moment derivative with respect to roll rate, 1/rad
c_{nr} = yaw damping derivative, 1/rad
c_y = side force coefficient, dimensionless
$c_{n\beta}$ = asymmetric side force derivative with respect to sideslip angle, 1/rad
c_{np} = side force derivative with respect to roll rate, 1/rad
c_{nr} = side force derivative with respect to yaw rate, 1/rad
g = gravitational constant, m/s^2
l_e = distance between the two engines centreline, m
l_x = distance between centre of gravity and aerodynamic centre along x-axis, m
l_z = distance between centre of gravity and aerodynamic centre along z-axis, m
l_{xe} = distance between centre of gravity and engine thrust centre along x-axis, m
I_x = moment of inertia about the roll axis, kgm^2
I_{xz} = cross product of inertia between roll and yaw axis, kgm^2
I_y = moment of inertia about the pitch axis, kgm^2
I_z = moment of inertia about the yaw axis, kgm^2
m = aircraft mass, kg
p = roll rate, rad/s
q = pitch rate, rad/s
$\underline{q}$ = dynamic pressure, N/m^2
r = yaw rate, rad/s
S = reference area, m^2
T = thrust, N
u = x axis speed in body axis system, m/s
v = y axis speed in body axis system, m/s
w = z axis speed in body axis system, m/s
α = angle of attack, deg or rad (AoA)
β = sideslip angle, deg or rad
δ_{vp} = pitch vector thrust angle, deg or rad
δ_{vr} = roll thrust vector angle, deg or rad
δ_{vy} = yaw thrust vector angle, deg or rad
6 = pitch angle, deg or rad
ϕ = bank angle, deg or rad

Introduction

The agility and the manoeuvrability play main role in designing fighter aircraft. An analytical investigation can give further detail on the characteristics of the aircraft. It could help the better understanding of the behaviour of the aircraft. It is important especially at the high angle of attack flying.

The high angle of attack mechanics could produce some nonlinear phenomena. Some studies(1)(2)(3)(4)(5)(6)(7) made on the high angle of attack flight mechanics. Bifurcations were found (1)(2)(3)(4)(5)(6) and even chaos(5)(6)(7) was observed. These phenomena could

cause problems in the flying and handling qualities. So it is very important to understand the nature of the aircraft's motion. It gives the possibility to avoid the accidents and better control system could be designed.
To reach the poststall regime that gives superiority in dogfighting thrust vectoring is used. This new way of control generates sufficient moments at low speed.
Early studies made about the longitudinal motion of a vectored thrust aircraft. This paper is an extension of those studies. It tries to give some additional information on lateral motion as well. The model contains all the important nonlinearities with hysteresis effects.

Mathematical model

The full 6-degree-of-freedom motion was modelled. None of the terms of the rigid body motion was neglected. But some factors considered minor, for example the effect of spinning rotors, the changing of the centre of gravity position and the density changing. The mathematical model based on a NASA wind tunnel test of F/A-18⁽⁸⁾. It uses analytical functions for the aerodynamic coefficients and all of them are the function of AoA. The coefficients are given at certain conventional control surface deflection and between them they are linearly interpolated. The full equation system is the following:

$$\dot{u} = rv - qw - g\sin\theta + X + \frac{T_x}{m} \tag{1}$$

$$\dot{v} = pw - ru + g\cos\theta\sin\phi + Y + \frac{T_y}{m} \tag{2}$$

$$\dot{w} = qu - pv + g\cos\theta\cos\phi + Z + \frac{T_z}{m} \tag{3}$$

$$\dot{p} = C_{41}pq + C_{42}qr + C43FR + C^*FP \tag{4}$$

$$\dot{q} = C_{51}pr + C_{52}(r^2 - p^2) + FQ \tag{5}$$

$$\dot{r} = C_{61}pq + C_{62}qr + C_{63}FP + C^*FR \tag{6}$$

$$L = \bar{q}Sc_D \tag{7}$$

$$D = \bar{q}Sc_L \tag{8}$$

$$X = \left[-D\cos a + L\sin a\right]/m \tag{9}$$

$$Y = \bar{q}Sc_y \tag{10}$$

$$Z = \left[-D\sin a - L\cos a\right]/m \tag{11}$$

$$FP = (\bar{q}SbC_l - ml_zY + T_zl_e)/I_x \tag{12}$$

$$FQ = (\bar{q}S\bar{c}C_m + m(l_zX - l_xZ) - T_zl_{xe})/I_y \tag{13}$$

$$FR = (\bar{q}SbC_n + ml_xY + T_yl_{xe})/I_z \tag{14}$$

$$c_L = c_{L0} + \frac{\bar{c}}{2V}(c_{Lq}q + c_{L\dot{\alpha}}\dot{\alpha}) \tag{15}$$

$$c_m = c_{m0} + \frac{\bar{c}}{2V}(c_{mq}q + cm_{m\dot{\alpha}}\dot{\alpha}) \tag{16}$$

$$c_y = c_{y0} + c_{y\beta}\beta + \frac{\bar{b}}{2V}(c_{yp}p + c_{yr}r) \tag{17}$$

$$c_l = c_{l0} + c_{l\beta}\beta + \frac{b}{2V}(c_{lp}p + c_{lr}r) \tag{18}$$

$$c_n = c_{n0} + c_{n\beta}\beta + \frac{b}{2V}(c_{np}p + c_{nr}r) \tag{19}$$

$$T_x = T\cos\delta_{vp}\cos\delta_{vy}\cos\delta_{vr} \tag{20}$$

$$T_y = T\cos\delta_{vp}\sin\delta_{vy}\cos\delta_{vr} \tag{21}$$

$$T_z = T\sin\delta_{vp}\cos\delta_{vr} \tag{22}$$

where

$$C^* = I_xI_z/\left(I_xI_z - I_{xz}^2\right) \tag{23}$$

$$C_{41} = I_{xz}\left(I_z + I_x - I_y\right)/\left(I_xI_z - I_{xz}^2\right) \tag{24}$$

$$C_{42} = \left(I_z\left(I_y - I_z\right) - I_{xz}^2\right)/\left(I_xI_z - I_{xz}^2\right) \tag{25}$$

$$C_{43} = I_xI_{xz}/\left(I_xI_z - I_{xz}^2\right) \tag{26}$$

$$C_{51} = \left(I_z - I_x\right)I_y \tag{27}$$

$$C_{52} = I_{xz}/I_y \tag{28}$$

$$C_{61} = \left(I_x\left(I_x - I_y\right) + I_{xz}^2\right)/\left(I_xI_z - I_{xz}^2\right) \tag{29}$$

$$C_{62} = I_{xz}\left(I_y - I_z - I_x\right)/\left(I_xI_z - I_{xz}^2\right) \tag{30}$$

$$C_{63} = I_xI_{xz}/\left(I_xI_z - I_{xz}^2\right) \tag{31}$$

Equations (15)-(19) contain the hysteresis effect. The (20)-(22) add the thrust vectoring terms. Avoiding the implicit using of the derivative of angle of attack sorted equations were used.

Simulation results

During the simulation all the control surfaces were fixed. First the equilibrium surfaces were investigated. The simulation results contain three different cases such as pure sideslip, steady turn with no sideslip and the full 6-degree-of-freedom motion.
The used model has some certain problems. The figure for the side force coefficient does not match with the function that should give it. The differences are obvious but it seemed not to cause strong effect on the model. The aircraft motion to the sideslip well damped but it has strong bank tendency even the side force coefficient was corrected according to the figure⁽⁸⁾.

Pure sideslip

The sideslip means steady motion with no angular velocities so p, q and r=0 and the derivatives have no effect on the model.
Figure 1 shows the equilibria of bank angle on the thrust and yaw thrust vectoring parameter space. The pitch thrust deflection is 3degrees. It gives similar results as ⁽⁹⁾. The aircraft needs quite strong roll control.

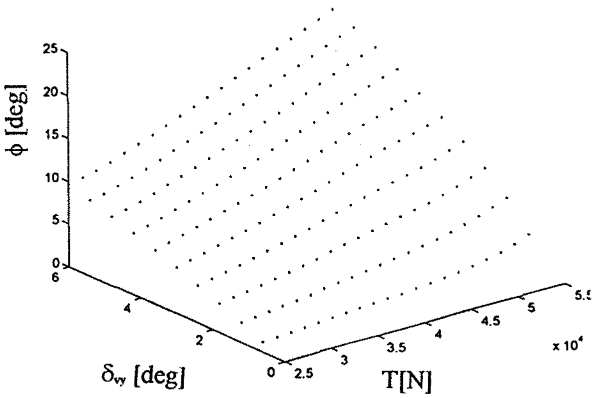

Fig.1.

Steady turn with no sideslip

Steady turn is given if the bank and pitch angle do not change. Further restriction made to separate the different cases and v=0 was added to the constraints. On Figure 2 the turn rate could be seen in deg/sec for different bank angle and thrust level.

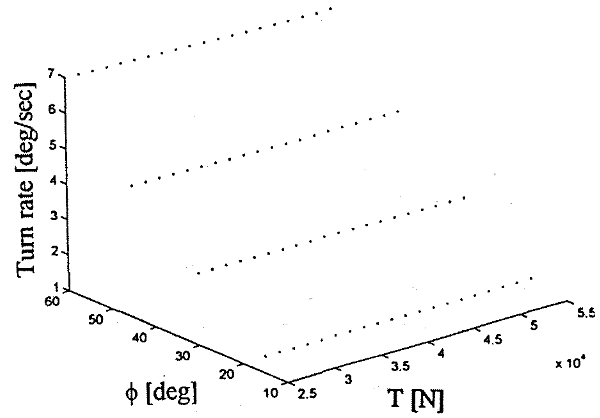

Fig.2.

6-Degree-of-Freedom Motion

Several simulations made for different thrust level and thrust deflections for all the directions. For a poststall stable equilibrium any disturbance leads chaotic motion that replaces the limit cycle oscillation called wing-rock. The equilibrium was the formerly well investigated T=35kN and δ_{vp}=10deg.

Figure 3.and 4. give the phase portrait of the motion on the angle of attack and sideslip and on the bank angle and roll rate plane.

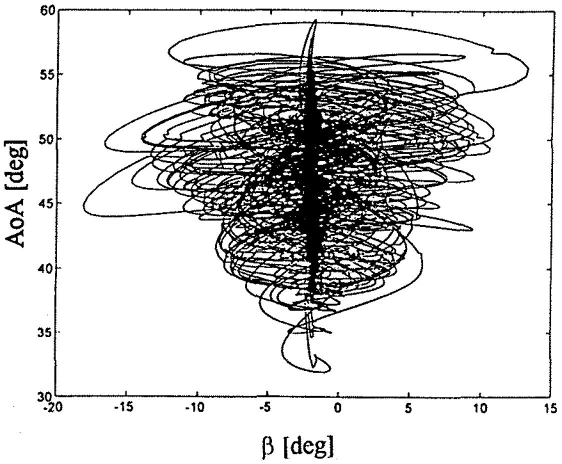

Fig.3.

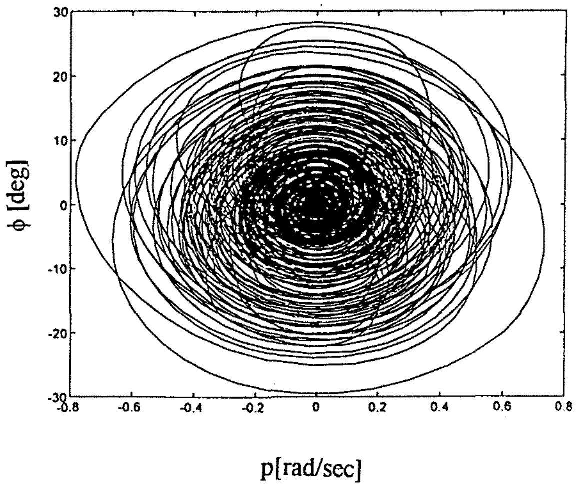

Fig.4.

Other interesting characteristics was observed that the chaos disappeared if there was any other control deflection and turned to wing rock.

The simulations give promising results as well. A poststall region can be reached in 3seconds from a level flight. Furthermore from a stable poststall equilibrium a 180 degrees turn could be performed in another 5seconds. The maximum theoretical turn rate without thrust vectoring at M=0.3 is 10deg/sec. All the controls were fixed during the simulation so a little sophisticated way the turn could be done in less time.

Conclusions

Continuing the investigation of high angle of attack flight mechanics gives further rich dynamics of the aircraft.

Chaotic motion was observed in the autonom 6-degree-of-freedom motion at a poststall equilibrium, but it disappeared if any lateral control were applied. Although this study does not consider the control system effects but it seems quite important to understand the interaction between the airframe and the control system. So the unwanted oscillations and even the chaos could vanish from the motion with a well designed control system. Additionally an analytical way could cover the whole flight domain.

It was also proved that a 180 degrees turn could be performed in 8 seconds with thrust vectoring and it is much less than the theoretical value

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