# APPLICATION OF ESTOL FLIGHT CONTROL TECHNOLOGY TO UCAV DESIGN

**A. Knoll, B. Fischer**
**EADS Military Aircraft**

**Keywords**: *flight control, ESTOL, control laws*

## Abstract

*During the X-31 Vector program the ESTOL technology (Extreme Short Takeoff and Landing) has been developed and will be flight tested. This technique uses very high angles of attack during takeoff and landing to improve the performance.*
*ESTOL might also offer the possibility to improve the airfield performance of unmanned combat air vehicles (UCAV). This report investigates the suitability of ESTOL for UCAV. Possible performance improvements are demonstrated with a potential UCAV design. The influence of the basic configuration is shown, as well as the integration into the basic control law structure.*

## 1 Introduction

The VECTOR program (Vectoring, ESTOL Control and Tailless Operation Research) is a joint project of the U.S. Navy and the German BWB (Bundesamt für Wehrtechnik und Beschaffung) together with the partners Boeing and the EADS Militärflugzeuge. This program is a follow on program of the X-31A project, which demonstrated enhanced maneuverability with angles of attack up to 70°.

Within the Vector project the fully automatic ESTOL landing will be flight tested. The use of high angles of attack (AoA) allows a significant reduction of the approach speed, without requiring changes of the configuration of the X-31. Shortly before touch down a derotation maneuver reduces the angle of attack to ensure sufficient ground clearance during touch down. This derotation maneuver is one of the main issues of the approach.

It was decided, that the use of ESTOL during the takeoff phase will not be demonstrated during the VECTOR program.

Modern UCAV design might use relatively high wing loadings for improvement of the high speed performance. To enable the flexible use of these aircraft from forward operating airstrips, short landing and takeoff distances are required. ESTOL offers the possibility to reduce these distances for a given configuration without adding complicated high lift systems.

## 2. The basic ESTOL maneuver

### 2.1 The ESTOL landing with the X-31

Figure 1 shows the basic configuration of the X-31. The Delta Candard configuration controls the pitch axis by the symmetric deflection of the wing trailing edge, by the canard deflection and by the vertical deflection of thrust vectoring vanes. The leading edges extend with a fixed correlation to the angle of attack. The lateral control is via the rudder, the diffential deflection of the trailing edge and the lateral deflection of the thrust vectoring vanes.

The ESTOL landing maneuver of the X-31 (figure 2) starts with the engagement of the ESTOL “autopilot”, which is an additional software within the flight control computer, interfacing with the basic control laws. The autopilot controls the aircraft along a given trajectory with flight path angles in the range of 3°, up to 6°, similar to an instrument landing system (ILS). During the initial phase of the approach the AoA is increased to selectable values and then kept constant, until start of the derotation maneuver. The speed is controlled by an autothrottle during the whole maneuver.

Since visual contact to the runway is no longer possible, the pilot uses a TV camera to monitor the approach. Additional head up display symbology informs the pilot on the active mode, as well as on deviations from the preplanned flight path.

Increasing the approach AoA results in a significant reduction of the necessary approach speed, as shown in Figure 3: increasing the standard X-31 approach AoA up to 30°, with a flight path angle $\gamma$ = -3° and a typical approach mass, reduces the approach speed by 60kt (=31m/s). With a landing mass of 14690lbs (=6660kg), this means a reduction of the landing roll from 8400ft to 3600ft (see ref. 1). As also shown in figure 3, even an increase of the AoA above the X-31's AoA for maximum lift further reduces the approach speed, since the steep nose up pitch attitude increases the vertical component of the thrust.

The disadvantage of a steep nose up pitch attitude, as with the X-31, is that the pitch angle $\theta$ is above the maximum angle allowed during touch down, which means touch down would result in a tail strike. To avoid this, the aircraft is automatically derotated, when the lowest point of the aircraft, typically the lower thrust vectoring vane, has a height of less than 2ft. During the derotation the pitch attitude is reduced to suitable angles for touch down, which means also a reduction of the AoA and of the lift. The unwanted result of this is an increase in vertical speed. Figure 4 shows the buildup to vertical speed during a typical derotation of the X-31.

To ensure maximum clearance during the derotation, the control laws change from a flight path control to a pitch attitude control, rotating the aircraft around the lowest point, the thrust vectoring vane, trying to keep a constant tail clearance.

## 2.2 The ESTOL Takeoff

The basic idea of the ESTOL takeoff was to use a ramp, similar to the skijump ramp used for the Harrier aircraft, to reach higher than normal AoA, initiating an early lift off. This ramp is of cause limited by the tail clearance of the aircraft. The reduction of the takeoff roll stems from the earlier rotation to a higher AoA than normal. The major requirement for this is an efficient control of the pitch moment at comparably low speeds. With the X-31 the pitch moment could be controlled by the thrust vectoring vane, which is, due to the high takeoff thrust, already during the takeoff roll very effective.

As mentioned above, the ESTOL takeoff is not part of the VECTOR program.

## 3. The problems of an ESTOL landing

The ESTOL landing is limited by several factors, which influence the use of the maneuver in different aircraft.

## 3.1 Vertical control power

The typical approach speed of a modern transport $V_{ref}$ overhead the runway threshold is:

$$V_{ref} = 1.3 \cdot V_S \qquad (1)$$

with $V_S$ as the stall speed, the stationary speed for level flight with the maximum lift coefficient $C_{L\,\max}$. This means, the maximum potential of speed reduction by using the ESTOL maneuver is under these conditions 30%.
Since lift is proportional to the square of the speed (with $r$ determining density and $S$ meaning wing area):

$$L = \frac{1}{2} r V^2 S C_L \qquad (2)$$

the pilot, if flying with $V_{ref}$ according to (1) and the corresponding AoA, could get a maximum lift of $1.3^2 = 1.69$ times the lift for level flight, by increasing the AoA up to the stall value. Therefore the pilot has a control power equivalent to 0.69g available for counteracting downward deviations form the flight path.

The approach with modern fighter aircraft is flown with a constant AoA, as a goal for the pilot, instead of an approach speed. With the X-31 this standard approach AoA allows for an increase of the lift up to 0.9g, in case upward corrections are required.

The ESTOL procedure uses this control power potential for reducing the approach speed, leaving no way to increase the aerodynamic lift. Therefore another way to create vertical forces for correcting deviations of the flightpath and for initiating flare maneuvers has to be found.

Several possibilities are available:

1. Increase of thrust. Due to the flat flight path angle of the X-31 during the approach, coupled with the big AoA's, the pitch angle of the X-31 aircraft is relatively steep, which results in a considerable vertical component of the thrust. If the thrust vanes are not deflected, the thrust of the X-31 creates no resulting pitch moment, therefore this method requires no additional reaction.
2. Increase of lift by changing the shape of the airfoil, e.g. deflecting the trailing edge flaps. This results in a change of the pitch moment, which could be eliminated by increasing the lift of the canard simultaneously.
3. Using thrust vector deflection to increase the vertical component of the thrust. This method also requires the increase of the lift of the canard to cope with the resulting moment.

An additional problem is that the effectiveness of the aerodynamic control surfaces is reduced with the slow approach speeds. These aerodynamic control surfaces are necessary for controlling the pitch attitude, especially for touch down. In contrast to normal operations these control surfaces are no longer used for manipulating the flightpath by changing the AoA of the wing, since near to maximum lift coefficient increasing the AoA no longer changes the lift effectively.

### 3.2 Reduced stability

Flight along the AoA for maximum lift means flying in a region with a reduced gradient of the pitch moment coefficient $\frac{dC_m}{da}$. For longitudinal static stability this gradient has to be:

$$\frac{dC_m}{da} < 0 \qquad (3)$$

meaning an increase of the counteracting pitch down moment after an increase of AoA (pitch up). For a otherwise longitudinal stable aircraft, this criterium might no longer be fulfilled near to maximum lift coefficient, meaning that the aircraft has a reduced pitch stability or even gets unstable. This increases the effort required for the flight control system, since the feedback gains now have to be scheduled with AoA to cope with the change in stability.

On the other hand this scheduling requires an accurate measurement of angle of attack. The X-31 uses a noseboom for this purpose. Operational configurations might not be able to use nosebooms due to stealth reasons or to avoid disturbances of the noseradar. For sensors close to the aircraft body acquiring accurate AoA measurements gets more difficult due to local airflow disturbances.

Operating near to maximum lift coefficient or even beyond this, also means operating on the backside of the power curve. This means the aircraft operates in a region, where during level flight, the drag increases with reduction of thrust (see figure 5). The effect of this is, if the aircraft is forced to continue with constant altitude, that a sudden reduction of speed results in an additional increase of drag, which reduces the speed further. This also holds true if the aircraft has to follow a given flight path during approach. This behavior could not be dealt reasonably with by a human pilot, but requires an autothrottle system.

## 3.3 The derotation maneuver

The derotation maneuver is imposed by the limited allowance for pitch angle during touch down. The tail clearance suggests an early derotation. Since, the touchdown speed increases during the reduction of the AoA, the gear limits for touch down speed require a late, or low, derotation.

From an energy point of view the speed at touchdown $V_1$ is depending on the initial conditions during initiation of the derotation: speed $V_0$ and height above the runway $h_0$, and of the forces thrust $F$ , lift $L$ and drag $D$ acting along the flightpath $s$ to the touchdown.

$$\frac{m}{2}V_1^{\,2} = \frac{m}{2}V_0^{\,2} + mgh_0 + \int \vec{F}d\vec{s} + \int \vec{L}d\vec{s} + \int \vec{D}d\vec{s} \tag{4}$$

Lift is per definition perpendicular to the speed, thus eliminating the influence of lift, while drag is parallel to the speed. If the thrust is inline with the reference axis of the AoA (figure 6), $F \cdot cos a$ is the component along the speed:

$$\frac{m}{2}V_1^{\,2} = \frac{m}{2}V_0^{\,2} + mgh_0 + \int (W + F\cos a)\cdot V dt \tag{5}$$

This equation shows, that the initial flight path angle during the initiation of the derotation is without influence on the kinetic energy during touchdown. The speed $V_1$ is a vector consisting of vertical speed $\dot{h}_1$ and of horizontal speed $V_{h1}$, thus the initial flight path angle $g_0$ defines together with thrust F(t) and AoA α(t) the ratio between both components of $V_1$.

The energy equivalent of the vertical speed will be absorbed by the shock absorber of the gear strut and the tires, while the energy equivalent of the horizontal speed will be absorbed by the brakes during the rollout. This means, that vertical speed is limited by the gear, while the horizontal component determines the landing performance, therefore a compromise between both constraints has to be found.

## 3.4 The approach path angle

A major factor on the derotation is the flight path angle during the approach. Two different extremes are possible (figure 7):

1. A steep approach angle allows for high AoA's with relatively flat pitch attitude, eliminating the need for a derotation. But the vertical component of the thrust, which might be increased for control of the vertical speed is reduced to nearly zero. This requires an additional means of controlling the vertical movement.
   The biggest disadvantage of this method is the fact, that the vertical speed is increased considerably with steeper flight path angles *g:*
   $$\dot{h} = V \cdot \sin(g) \tag{6}$$
   while the control power available to initiate a flare maneuver is reduced.
2. A relatively flat approach requires a steep nose up pitch attitude to reach high angles of attack. This increases the vertical component of the thrust and thereby allows for a big influence of thrust on the vertical speed during disturbances. The vertical speed is low, due to small values of the flight path angle *g*. On the other hand, the steep pitch angles require a pronounced derotation maneuver, which results in an increase of the vertical speed during touch down.

## 3.5 The navigational accuracy

The derotation maneuver requires a precise navigation system, with an accurate information on the height above the terrain. Height is calculated from the comparison of a terrain model with the altitude (above sea level), which is measured by a sensor. Since the profile of the runways is typically not flat, at least to avoid standing water, the influence of the terrain model is significant. This means, that a geometric survey has to be made for every runway, which will be used for a X-31 type of derotation maneuver.

The altitude measurement of a standard civil GPS receiver does not measure the altitude with sufficient accuracy, therefore the Integrity Beacon Landing System (IBLS®) of IntegriNautics was chosen for the VECTOR program. This system gives an altitude accuracy of less then 4 inches, based on a differential GPS system. This means, that every airport which might be used for such a landing, must be within the reach of differential GPS transmitter.

## 4. The ESTOL control laws

### 4.1 The Longitudinal Axis during Approach

The X-31 control laws give a good example for a potential implementation into a UCAV design, due to the fact, that one of the main goals was to use the basic control laws as far as possible.

The basic structure is a system with feedforward (direct link) for the stationary values, and with feedback for controlling deviations.

The feed forward is scheduled with the distance to the derotation point.

The control effectors are:

- Symmetric trailing edge
- Candard deflection
- Thrust vectoring deflection
- Power lever angle

Flying in the high AoA regime requires the feedback of

- AoA: proportional and integral
- Pitchrate: proportional

For the control of the ESTOL approach path additionally the following values were fed back:

- Flightpath angle: proportional
- Height: proportional and integral

Height is required since flightpath angle gives no absolute reference to the present position. The speed results out of the above mentioned parameters. With the X-31 short term deviations of the speed are also controlled.

This system would also be well suited for a UCAV of similar configuration.

### 4.2 The Longitudinal Axis during Derotation

As already mentioned the pitch angle θc is controlled to keep the height of the lowest point of the aircraft (thrust vectoring vane at the tail) constant. $\dot{q}$ is therefore commanded in order to keep the vertical speed of the lowest point to zero.

$$\dot{q}_C = \frac{V \cdot \sin(g)}{R_{TAIL} \cdot \cos(q_0 + q_{TAIL})} \qquad (7)$$

Figure 8 shows the corresponding geometry.

If the design of a UCAV landing gear, together with the tail geometry and an effective vertical force effector, allows to use a steep ESTOL approach angle, as described earlier, the derotation might be no longer necessary. In this case this part of the control laws might be replaced with a control of vertical touchdown speed $\dot{h}_1$.

### 4.3 The Lateral Axis

The control of the lateral axis during the approach phase is relatively simple. Within the X-31 project the basic control laws use a feedback of:

- Flightpath fixed rollrate $p_k$ :proportional
- Yawrate *r*: proportional
- Sideslip angle *b*: proportional

For the ESTOL approach the commanded values for these parameters are not given by the pilot's controls as normal, but are calculated out of these values:

- Lateral flightpath deviation *DY*
- Track angle deviation: *Dc*
- Flightpath bank angle: *Dm*

During the derotation the control laws have to change, to enable a touchdown within the configurational limits. The operational limitations define wether a special maneuver is required to align the aircraft with the runway heading immediately before touchdown, for example the standard wing low procedure. The use of abrupt maneuvers is limited due to difficult aerodynamic conditions near maximum lift coefficient.

## 5. Use of ESTOL for an UCAV

The use of the ESTOL technique for an UCAV implies two basic requirements to the configuration:

1. Control power for stabilization and rotational control, which means sufficient control moments
2. Controllability of the flight path, which means sufficient control forces

For the following evaluations an example UCAV design was chosen: the FTT-U configuration as proposed during a German research project in the late 90’s with an additional thrust vectoring vane. This aircraft is a delta configuration with a mass of 3080lbs (=1400kg) and a wing area of 155ft$^2$ (=14,4m$^2$ ). Figure 9 shows the possible reductions in approach speed for this configuration.

### 5.1 Control power for stabilization

The question of stabilization can be solved with the usual linear methods (Nichols plot etc.), assuming a suitable dynamic model of the aircraft, the controller and the actuators. Of more importance in this context is the requirement for sufficient moment control power, which is expressed with the available maximum pitch acceleration $\dot{q}$. This control potential contains two contributions:

1. The aerodynamic effectors, with a maximum moment decreasing with square of speed.
2. The pitch moment induced by a deflection of the thrust vectoring vanes. An additional increase of thrust is deemed to be to slow for momentum control.

Figure 10 shows the resulting pitch acceleration for both effectors as a result of flight speed for the given example UCAV. The effectivity of the aerodynamic effectors (trailing edge flaps) deminishes with the square of the speed, as expected (full line). The effectivity for the thrust vectoring vane is shown for a deflection of 20° with the trimmed thrust necessary for a steady $\gamma$=-3° approach for the corresponding AoA. Since the necessary trimmed thrust increases with AoA, the achievable pitch acceleration increases with deminishing speed. This indicates, that for effective control during the ESTOL phase thrust vectoring vanes are necessary. Increasing the aerodynamic surfaces in size is not efficient, especially for the cruise phase.

The available pitch moment of the thrust could even be increased by a higher stationary thrust. This would be possible by increasing the drag, for example with speed brakes at the fuselage. Since the reaction of such speed brake might be faster, than increasing the thrust, retracting these could also to manipulate the speed axis.

### 5.2 Control power for flightpath control

Figure 11 shows the X-31 when passing a vertical gust of 17ft/s (5m/s) (assumed to be of rectangular shape for worst case considerations). The initial result of the vertical gust would be for an uncontrolled aircraft, with a wind speed of $V_W$ , a reduction of the angle of attack by $Da$:

$$\Delta a \approx \arcsin(\frac{V_W}{V}) \qquad (8)$$

assuming a small flight path angle $\gamma$ and neglecting the minimal influence on initial speed $V$. Formula (7) means that the influence on AoA increases with decreasing speeds. The result of this is a change in lift as well as in drag.

If the lift is linearized around the initial value 0, the resulting change in lift is:

$$\Delta L = \frac{r}{2} V^2 S \left[\frac{dC_L}{da}\right]_0 \cdot \Delta a \qquad (9)$$

Within the vicinity of maximum lift coefficient the gradient of the lift coefficient vs. AoA vanishes (see figure 12 for the X-31), thereby reducing this effect (as seen in fig. 11). Formula (8) also shows, that if $\Delta\alpha$ is assumed to be small, the influence on lift diminishes with smaller speeds:

$$\Delta L = \frac{r}{2} V \; S \left[ \frac{dC_L}{da} \right]_0 \cdot \frac{V_W}{V} \qquad (10)$$

The equivalent equation is also true for the drag. Since the gradient of the drag coefficient vs. AoA does not vanish near to maximum lift coefficient, the drag influence during gusts is significant.

With the chosen example UCAV an ESTOL approach with a flightpath angle of -3° and a AoA of 25° requires a thrust of 37% of the weight. With the resulting pitch up attitude of 22° the vertical component of the thrust is 14%. This means, if the thrust to weight ratio is 1, that an increase of the initial thrust values of 37% up to a maximum of 100% results in a vertical acceleration of 0.63g, thus equaling the vertical control power of a conventional approach.

Comparing this value with the factor 0.69g, as used above for conventional aircraft, indicates a sufficient margin for flightpath control. The basic assumption here is, that the dynamics of thrust increase is fast enough to deliver this acceleration in an acceptable time.

## 6. Conclusion

The investigation has shown, that ESTOL is an effective way of improving the landing performance of UCAV. A necessary requirement for this is an effective thrust vectoring system. If vertical speed during touch down is limited by the landing gear, a shallow approach is advisable, resulting in a relatively steep nose up attitude. This increases the effectivity of the thrust for vertical control, but also requires a special derotation maneuver for touch down, as long as the allowable touch down attitude is restricted by tail clearance.

## References

[1] Selmon J., White S., Sheen J., Bass D. and Miranda L. High Angle of Attack Autonomous Landing using the X-31A Aircraft. AIAA Guidance Navigation and Control Conference and Exhibit, Montreal, AIAA 2001-4207, 2001.

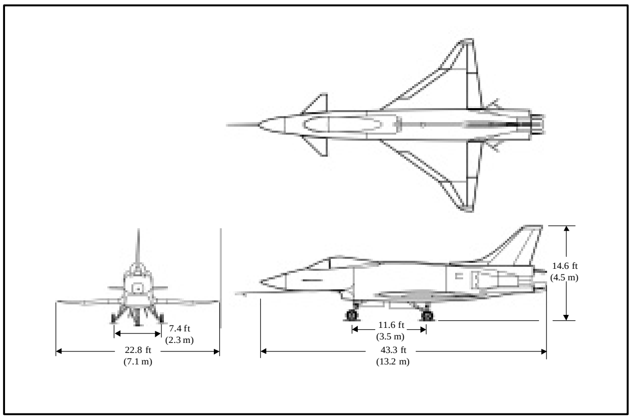

**Fig. 1:** X-31A Configuration

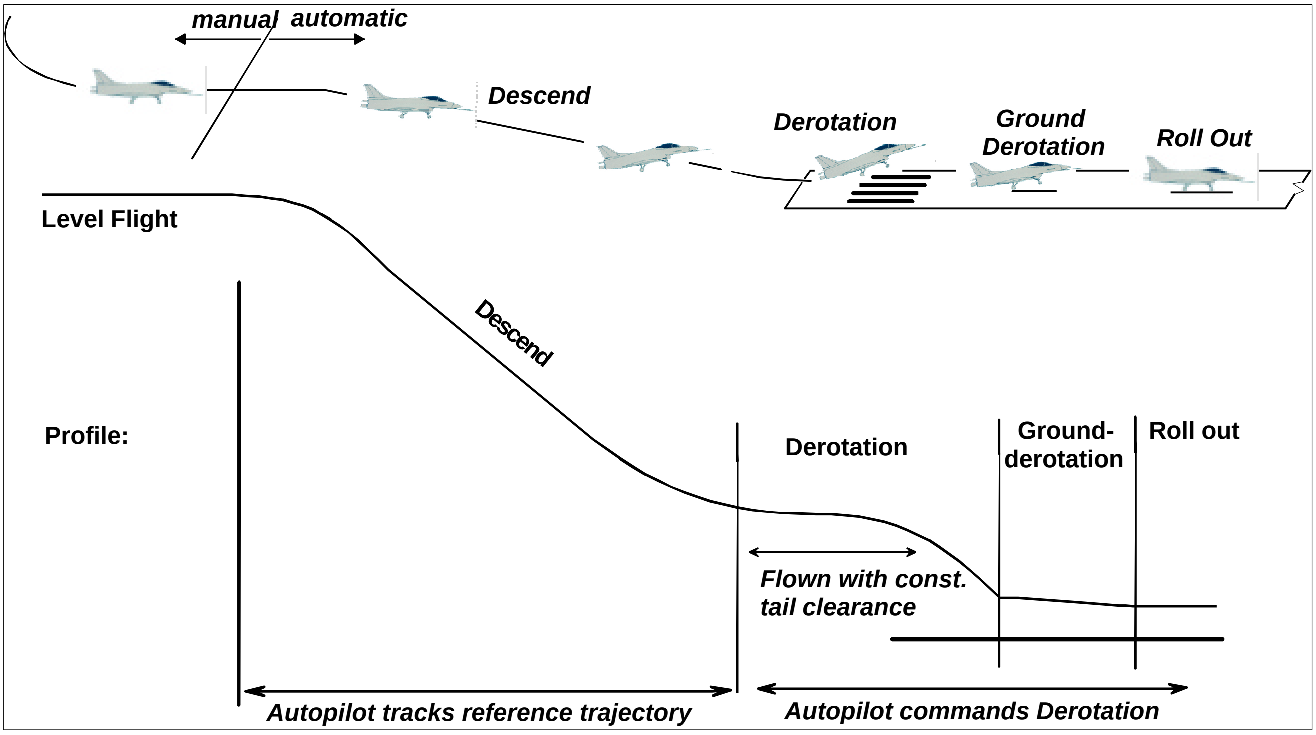

**Fig. 2:** ESTOL landing maneuver of the X-31

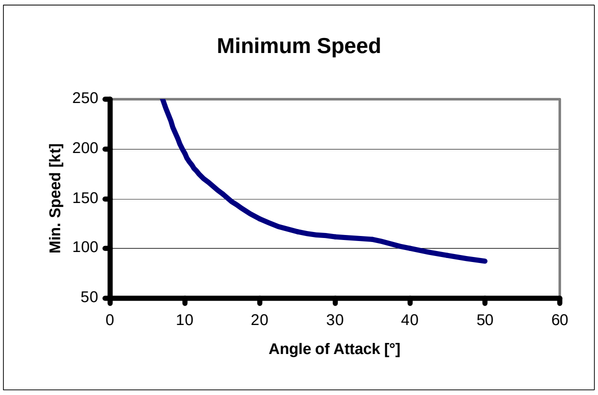

**Fig. 3:** Reduction of X-31 approach speed by increasing the approach AoA

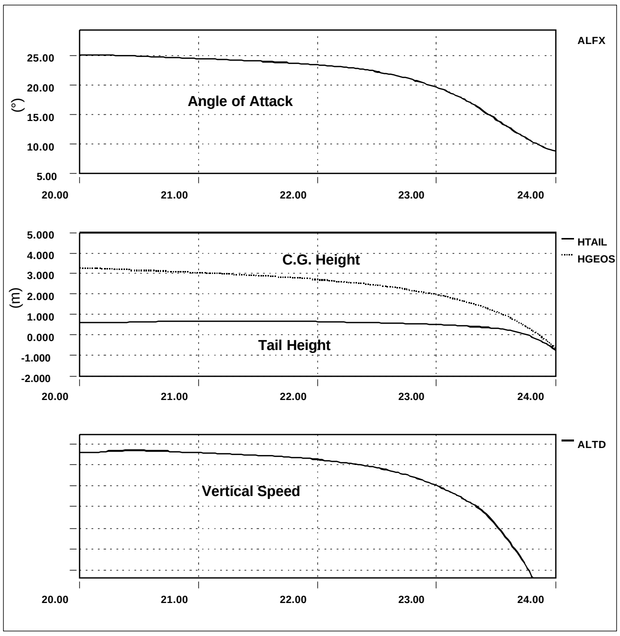

**Fig. 4:** Time history of AoA $a$, C.G. height, tail height and vertical speed $\dot{h}$ (negative due to downward motion)

**Fig. 5:** Required thrust vs. speed for level flight (X-31)

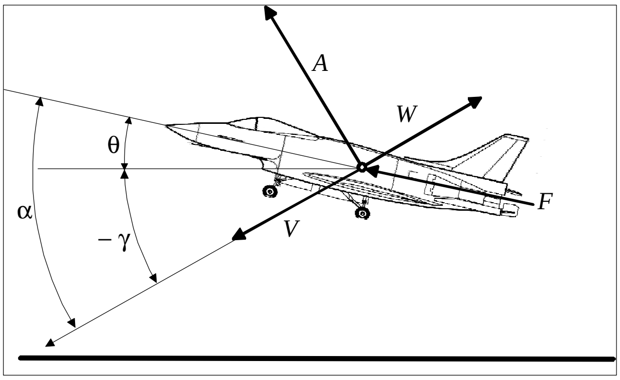

**Fig. 6:** Forces acting during derotation

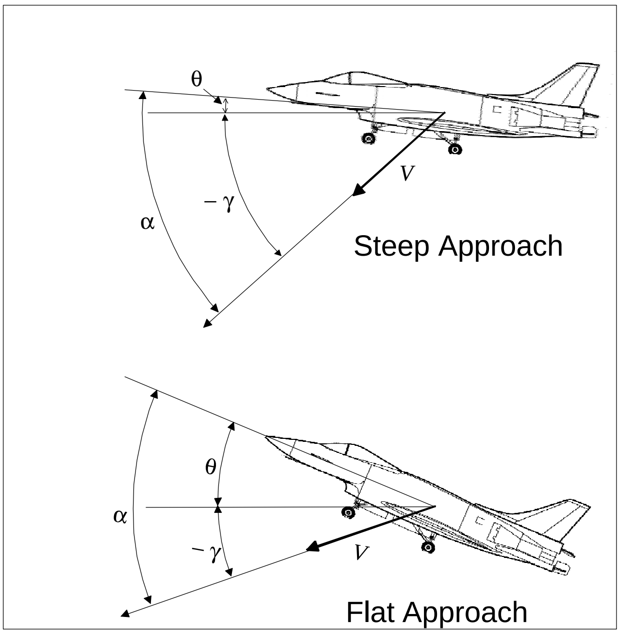

**Fig. 7:** Steep approach vs. flat approach

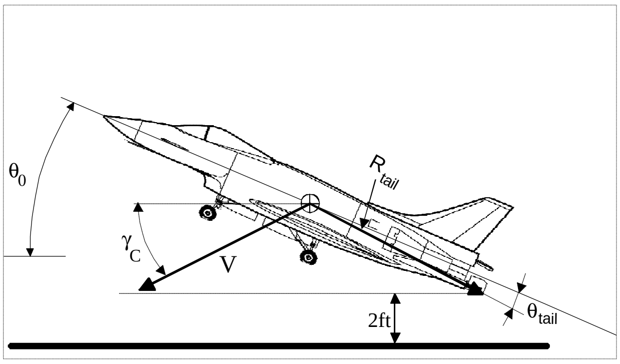

**Fig. 8:** Geometry during derotation

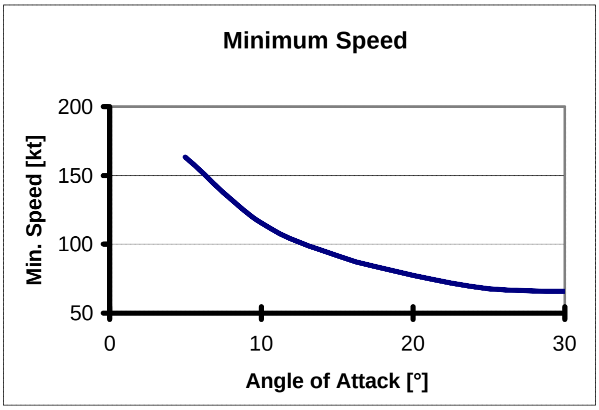

**Fig. 9:** Approach speed reduction for an UCAV

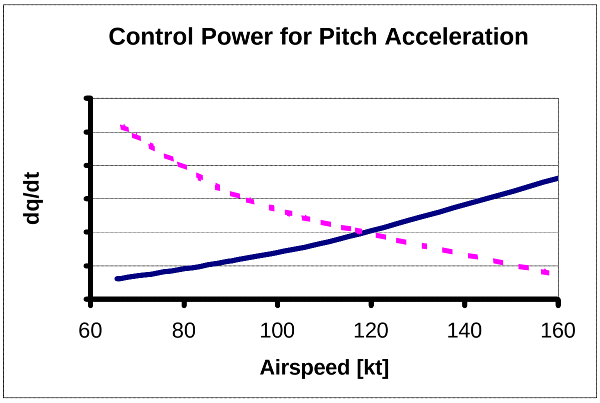

**Fig. 10:** Maximum achievable pitch acceleration due to deflection of the aerodynamic surfaces η (bold line) and thrust vector vane deflection δ (dashed line)

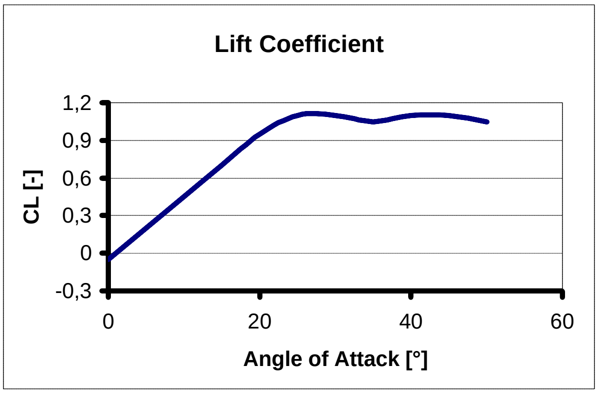

**Fig. 12:** Lift coefficient $C_L$ vs. angle of attack $a$

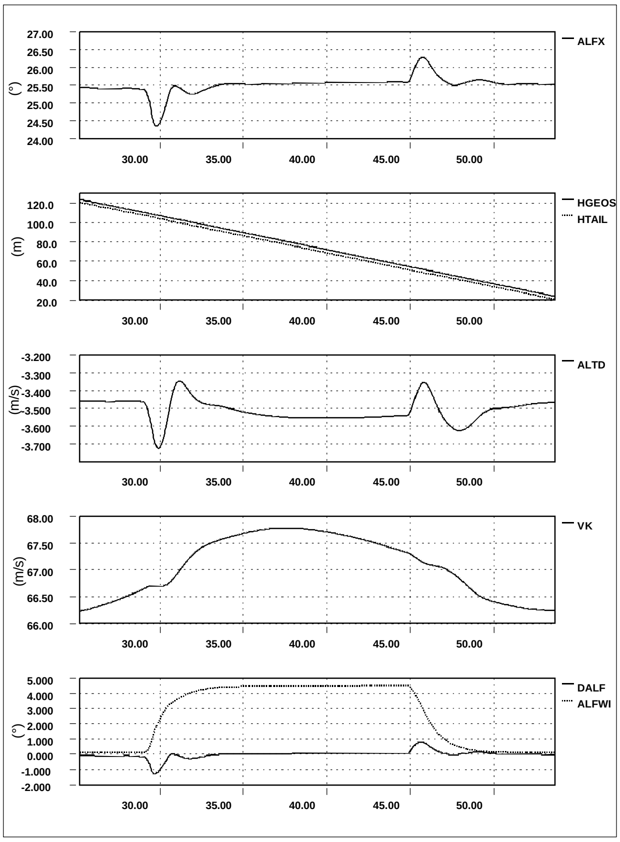

**Fig. 11:** Time history of the X-31 when passing a vertical gust of 5 m/s (17 ft/s), shown are:

- angle of attack
- CG-heigth and tail height
- vertical speed
- airspeed
- internal AoA of the system