ANALYSIS OF CONSTANT TIME DELAY AIRBORNE SPACING BETWEEN AIRCRAFT OF MIXED TYPES IN VARYING WIND CONDITIONS

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Abstract

This study analysed the performance of constant time based airborne spacing under different operational conditions using fast time simulation. The effects of time based spacing criteria, mixed aircraft types and wind conditions on the ability of an aircraft to maintain a time spacing behind a descending lead aircraft were investigated. The spacing performance of a previously used approximate time delay spacing criterion based on current lead aircraft speed was compared with an exact time delay spacing criterion based on lead aircraft position history. The exact time delay spacing criterion resulted in smaller time delay spacing errors and smoother true airspeed behaviour.

The exact time delay (60 s) criterion was then used to compare the spacing performance of a heavy aircraft following a light with a heavy aircraft following a heavy for different wind conditions. The results show that a heavy aircraft followed a light with approximately 40 % more maximum time spacing error than a heavy aircraft followed a heavy.

Different effects for constant and turbulent winds were observed. Maximum spacing error increased slightly with constant wind speed but always remained within 10 s up to maximum constant wind speeds of 87 knots (at 30 feet altitude) and 235 knots (at 29,000 feet altitude). Turbulent winds severely degraded stability particularly in cross wind conditions.

Introduction

Airborne spacing is a promising area of air traffic management research where air traffic controllers retain responsibility for keeping aircraft separated but can, where appropriate, delegate pair wise spacing related tasks to the flight deck [2]. Information to support these tasks, such as identification, position and velocity of the other aircraft, could be transmitted by new air-to-air surveillance technology e.g. Automatic Dependent Surveillance Broadcast (ADS-B).

An interesting application of airborne spacing currently under investigation is 'remain behind' [3] where air traffic controllers may request pilots to maintain a given along track distance or time behind a lead aircraft. Time based spacing could have benefits operationally because it may allow air traffic controllers to give spacing instructions to aircraft at high altitude that remain applicable throughout the descent down to the final approach. Limiting constraints such as runway occupancy, wake vortex decay and human reactions may be more naturally expressed in terms of time rather than distance and therefore more compatible with a time based spacing instruction.

Time based spacing criteria were introduced in an exact form by [12] and further used by [1] (and references therein). An approximate time based spacing criterion was also used in several studies e.g. [6][11][13]. Most studies reviewed tended to assume similar aircraft performance [10][13] and simple constant wind models [6]. This study therefore focused on (i) comparing approximate and exact time based spacing criteria, and (ii) using exact time based spacing to investigate the effects of a combination of aircraft type mix and more realistic wind model on spacing performance.

The paper is organised as follows: the spacing criteria and guidance law of time based spacing are presented, followed by a definition of the environment model including wind and aircraft models. The evaluation method describes the test scenarios, metrics and range of experimental

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parameters used. Results for (i) and (ii) above are presented as a series of graphs followed by a conclusion.

Time based spacing

Constant time delay (CTD) spacing criteria

Time based airborne spacing was considered where an aircraft kept a CTD behind a lead aircraft. Below are presented the two structures of the CTD spacing introduced in [12], the exact CTD criterion, and an approximate CTD criterion.

Exact CTD Criterion: The exact CTD criterion defines spacing error ($t_{errorCTD}$) as the difference between the elapsed time since the lead aircraft over flew the current trailing aircraft position, and the desired time spacing ($t_{spacing}$):

$$t_{errorCTD} = t - t^{*}|_{y_{lead}(t^{*})=y_{trail}(t)} - t_{spacing} \quad (1.1)$$

The exact CTD criterion can be rewritten as an equivalent constant distance-based criterion:

$$y_{errorCTD}(t) = y_{lead}(t - t_{spacing}) - y_{trail}(t) \quad (1.2)$$

The re-formulation of the CTD criterion as a constant distance criterion was used in the design and implementation of the guidance law controller.

Approximate CTD Criterion: Assuming any changes in the lead ground speed V_{leadGS} were slow, the above exact CTD criterion was approximated by:

$$t_{errorCTD} = \frac{y_{lead} - y_{trail}}{V_{leadGS}} - t_{spacing} \quad (1.3)$$

The approximate CTD criterion can be rewritten as an equivalent distance-based criterion:

$$y_{errorCTD} = y_{lead} - y_{trail} - y_{distCTD} \quad (1.4)$$

where:

$$y_{distCTD} = V_{leadGS} \cdot t_{spacing} \quad (1.5)$$

The approximate CTD criterion was used in several references for simplicity of calculation when the lead aircraft airspeed was constant or varied slowly. The exact CTD criterion required the position time history of the lead aircraft (see [1]) and the exact time spacing error given in equation (1.1), which was more difficult to compute than the corresponding distance spacing error. This led to a more complicated implementation in Matlab/Simulink models.

CTD spacing guidance law

The spacing guidance law aimed at maintaining a given CTD spacing along the track to a lead aircraft through speed adjustments as a pilot or cockpit automation might do. The guidance law was designed to provide a calibrated airspeed (CAS) reference to the basic autopilot. Target altitude and target track were fed independently.

The control law was of the form (in the Laplace domain):

$$V_{CMD} = V_{trail_{TAS}} + (K_p + \frac{K_d s}{1+\tau s}) y_{errorCTD} \quad (1.6)$$

A spacing error compensation term was added to the current true airspeed of the trailing aircraft $V_{trail_{TAS}}$ and then converted to a CAS command V_{CMD}. In this implementation, K_p, the range error gain, was set to 0.03 (for smaller values the guidance law time response became too large). K_d, the differential gain, was set to 1.5 (for smaller values, the guidance became unstable, and for larger values, stability was achieved but with large oscillations). To avoid an unrealisable control system where differentiation of the error was required, the differential term $K_d s$ was approximated by using a rate filter with a lead time constant τ equal to 0.01 seconds. The structure of this guidance law (1.6) was the same as that used in the air traffic simulator for airborne spacing real time simulations at Eurocontrol for the Co-Space project [3].

Environment model

Wind model

The wind model was based on that of the Joint Aviation Requirements All Weather Operations (JAR-AWO) autoland certification process [5].

Figure 1 presents the wind model implemented within Matlab. The turbulence provided has a

Gaussian distribution, conforming to the Dryden spectrum. The turbulence provides disturbances of the airspeed and angle-of-attack.

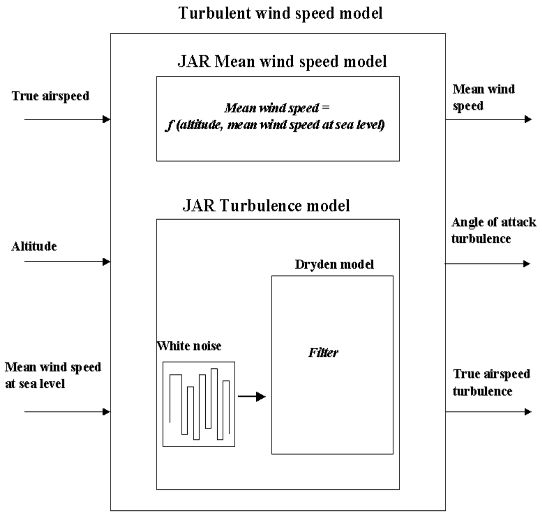

Figure 1. The wind model components

In this model the average wind speed was altitude dependent, and directly associated with the wind as measured at 30 feet AGL (Above Ground Level). The average wind speed determined the turbulence intensity, and the wind speed increased with altitude (Figure 2).

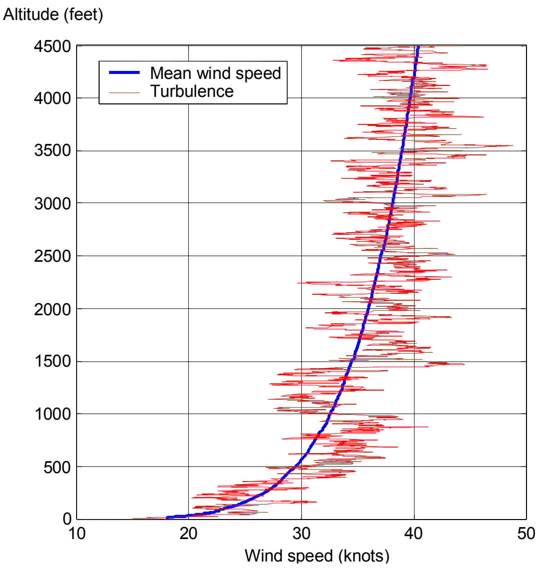

Figure 2. Turbulent wind versus altitude - JAR-AWO model (20 knot wind at 30 feet)

Table 1 summarises different values for the mean wind speed varying with altitude for a given initial value measured at sea level (30 feet).

Altitude AGL (feet)	Mean wind speed (knots)		
30	10	40	90
3,000	19	76	162
10,000	22.5	90.5	191.2
15,000	24	96	210
20,000	25	100	223
25,000	25.8	103	235
29,000	26	105	240

Table 1. Mean wind speed increasing with altitude and function of wind measured at 30 feet

Aircraft model

The aircraft model included the basic equations of motion, aerodynamic model, engine model, auto-pilot, auto-throttle control system, aircraft sensors and air-data model. The aircraft model was based on point mass equations of motion but with additional realistic rotational dynamics about the centre of gravity. The model included lateral motion of the centre of gravity and dynamic characteristics of the engines. A detailed description can be found in the Appendix. This study assumed a perfect airborne surveillance transmission of lead aircraft position and speed to the trailing aircraft, i.e. continuous update rate, no latency and perfect accuracy.

Evaluation method

Simulation environment

The following tests involved a pair of aircraft: a trailing aircraft following a lead aircraft in descent. The lead aircraft, trailing aircraft, spacing guidance and wind models were simulated using the Matlab/Simulink environment.

Comparing approximate and exact CTD spacing criteria

Test scenario

The lead aircraft followed a predefined flight plan from cruise to descent and the trailing aircraft adjusted speed to maintain the desired time spacing (60 s). Both aircraft started at an altitude of 29,000 feet and 7 Nm/min true airspeed (272 knots CAS) and descended to 10,000 feet. The aircraft started their descent at the same location after 10 Nm of flight (fixed top of descent). After 5 minutes the lead aircraft reduced CAS from 272 knots to 230 knots. The aircraft (Boeing 747-400) were initialised at the desired spacing. Wind was zero for all altitudes. The masses of both aircraft were initialised to 271,472 kg.

Metrics

The two metrics used were true airspeed behaviour and along track time delay spacing.

Experimental parameters

The experimental parameters under investigation were exact CTD spacing criterion and approximate CTD spacing criterion.

Exact CTD spacing criterion with mixed aircraft types and winds

Test scenario

The lead aircraft followed a predefined flight plan from cruise to descent and the trailing aircraft adjusted speed to maintain the desired time spacing (60 s). Both aircraft started at an altitude of 29,000 feet and 7 Nm/min true airspeed (272 knots CAS). The aircraft started their descent to 3,000 feet at the same location (10 Nm from start at fixed top of descent). At 25,000 feet the lead aircraft reduced CAS from 272 knots to 242 knots. Both aircraft had a track change from 90° to 45° at the same location (90 Nm from start) and the lead aircraft performed a second CAS reduction from 242 knots to 212 knots after this change of track.

The aircraft were initialised at the desired spacing. After the first 5 Nm of flight without wind, a JAR-AWO wind was introduced.

Metrics

The time delay spacing error between aircraft along-track was recorded.

Experimental parameters

A mixture of aircraft types and wind conditions were varied as indicated in Table 2:

Parameters		Values	
Aircraft type mix	**Leader**	Heavy	Light
	Trailer	Heavy	Heavy
Wind conditions	**Speed range**	0 to 87 knots at 30 feet (0 to 235 knots at 29,000 feet)	
	Initial direction	Cross	
		Tail	
		Head	
	Type	Constant	
		Turbulent	

Table 2. Exact CTD experimental parameters

A Boeing 747 model (initial mass 271,472 kg) was used for the heavy aircraft type and a Fokker 100 model (initial mass 37,919 kg) for the light aircraft type. Results for wind with turbulence involved many random trials to identify those with the minimum spacing performance.

Results

Comparing approximate and exact CTD spacing criteria

Figures 3 and 4 show how the true airspeed varied with time for both CTD spacing criteria. Non-optimal behaviour was observed for the approximate CTD criterion when the lead aircraft decreased speed. Reduction in the lead aircraft speed resulted in the approximate CTD criterion spacing error momentarily increasing. The trailing aircraft tried to reduce the error by increasing its own speed. As a consequence, the trailing aircraft

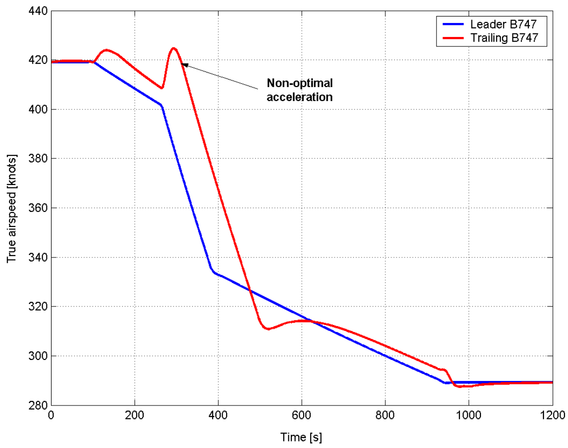

Figure 3. Approximate CTD criterion – true airspeed behaviour

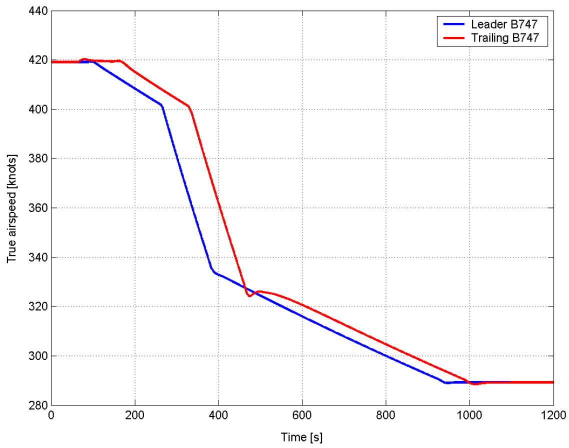

Figure 4. Exact CTD criterion - true airspeed behaviour

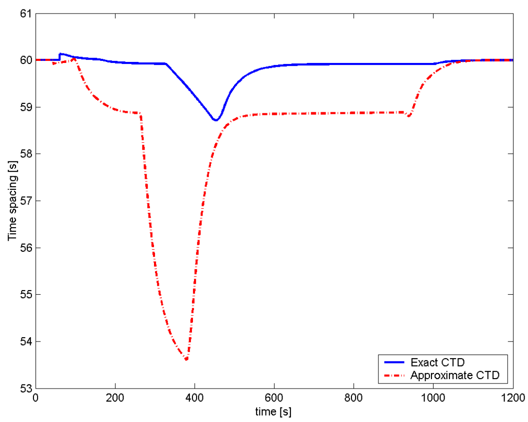

Figure 5. Approximate and exact CTD criteria - time spacing

accelerated sharply then decelerated in order to match the lead aircraft speed profile. This speed peak of 15 knots is clearly shown in Figure 3, and is unacceptable from an operational point of view.

Figure 5 shows the exact CTD criterion produced a smaller time spacing error (1.5 s) than the approximate CTD criterion (6.5 s). It should be noted that time spacing was measured using equation (1.1) for both criteria. The reaction times for the two CTD criteria were different. The approximate CTD criterion reacted at the instant when the lead aircraft changed speed (see equation (1.4)), whereas the exact CTD criterion reacted with a 60s delay (see equation (1.2)).

Based on the exact CTD criterion's smoother true airspeed behaviour and smaller spacing error, it was selected for further investigations.

Exact CTD spacing criteria with mixed aircraft types and winds

Figures 6, 7 and 8 show the along track time delay spacing errors for a heavy aircraft following a heavy, and heavy aircraft following a light, in tail, head and cross winds (constant and turbulent). A heavy aircraft followed a light with at least 40 % more maximum time spacing error, than a heavy aircraft following a heavy. This tendency confirmed expectations since the lighter aircraft was more easily accelerated and decelerated by the wind changes and therefore presented a more dynamic target to follow than the more massive aircraft.

Constant wind produced a steady maximum spacing error, which slightly increased with altitude. This error evolution was well controlled by the guidance algorithm without significant oscillation for large wind magnitudes. Spacing errors were kept to less than 10 seconds up to maximum constant wind speeds of 87 knots at 30 feet AGL (i.e. a wind speed of 235 knots at 29,000 feet).

4,500 random trials were performed with various turbulent wind conditions. Dotted lines in figures 6, 7 and 8 show that turbulence severely degraded stability. Turbulent tail and head winds produced similar effects on maximum spacing errors but turbulent cross winds had considerably more impact on the CTD spacing stability. The time

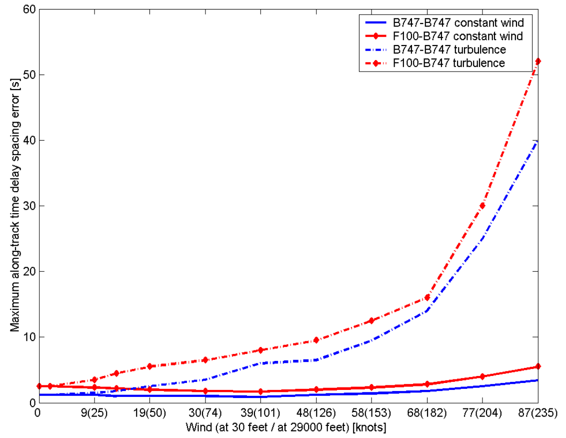

Figure 6. Tail wind effects on CTD spacing

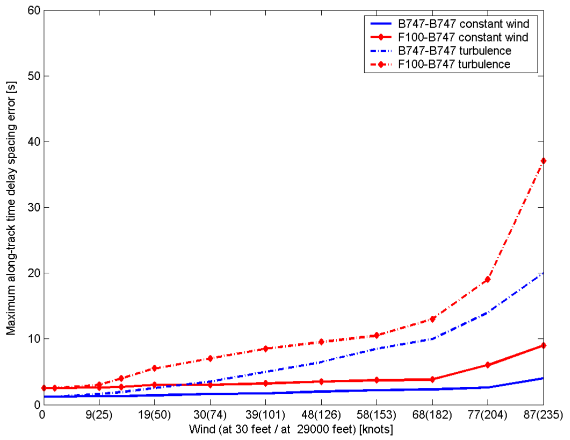

Figure 7. Head wind effects on CTD spacing

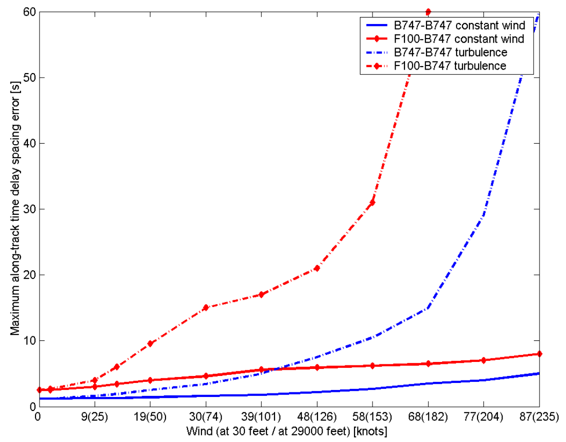

Figure 8. Cross wind effects on CTD spacing

delay spacing error remained below 10 s for maximum turbulent tail and head winds of 126 knots at 29,000 feet and for a maximum turbulent cross wind of 51 knots at 29,000 feet.

A possible reason for turbulent cross winds having more effect on the maximum along track spacing error could be that the cross-track guidance was perturbed more and due to the coupling effect with significant differences between track angle and heading angle, reduced the effectiveness of the along track guidance.

Conclusion

The effects of constant time delay (CTD) spacing criteria, mixed aircraft types and wind conditions on the ability of an aircraft to maintain a CTD spacing behind a descending lead aircraft were investigated using fast time simulation. The spacing performance of a previously used approximate CTD criterion based on current lead aircraft speed was compared with an exact CTD criterion based on lead aircraft position history. The exact CTD criterion was found to give the better spacing performance in terms of true airspeed smoothness and spacing errors. The exact CTD (60 s) criterion was then used to compare the spacing performance of a heavy aircraft following a light with a heavy aircraft following a heavy for different wind conditions.

The results show that a heavy aircraft followed a light with at least 40% more maximum time delay spacing error than a heavy aircraft following a heavy. Maximum spacing error sightly increased with constant wind speed but always remained within 10s up to maximum constant wind speeds of 87 knots (at 30 feet altitude) and 235 knots (at 29,000 feet altitude).

Turbulent winds severely degraded spacing stability particularly in cross wind conditions. The time delay spacing error remained below 10 s for maximum turbulent tail and head winds of 126 knots at 29,000 feet and for a maximum turbulent cross wind of 51 knots at 29,000 feet. Cross-track perturbations appear to have more impact on the relative along track spacing performance than along track perturbations, possibly due to a coupling effect between cross-track and along track guidance for significant differences between track angle and heading angle. It should be noted that this effect was observed for the maximum along track spacing error. Further research could consider the effect of turbulent wind direction on the mean along track spacing error

The spacing performance obtained here is suspected to be quite conservative since a basic guidance law was used. Future work could consider more advanced guidance laws including double differentiation and integral terms to improve robustness. The effect of mixed aircraft types on airborne spacing in aircraft pairs could be extended to chains of aircraft with different time spacing. Compounding effects of airborne surveillance transmission quality such as update rate, latency and accuracy could also be investigated.

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Keywords

Air traffic control system airborne time spacing wind aircraft type

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Appendix: Aircraft model

For this study, an aircraft model was required with realistic behaviour along typical descent profiles, including speed and heading changes, and intermediate altitude steps. The aircraft model is divided into two parts:

- The *aircraft dynamics* models the actual physics of the system.
- The *pilot model* is a combined representation of the aircraft auto pilot system and to a certain extent of the pilot actions on it.

For the aircraft dynamics, the following general assumptions are made:

- Flat, non-rotating earth.
- Standard atmosphere.
- Fully co-ordinated flight. The sideslip angle β is always zero and there is no side force.

The equations of motion used for the aircraft model are based on the three-dimensional point-mass differential equations, as found in many references [9][8]. The total set of differential equations results in 7 state variables, [γ V h φ ψ x_{east} x_{north}], where: γ is the flight path angle, V the true airspeed, h vertical distance or altitude, φ is the bank angle, ψ the heading angle, x_{east} the east position and x_{north} the north position and m the aircraft mass. Because the aircraft mass is not considered to be constant, the equations of motion are complemented by an eighth equation, describing the loss of mass due to the fuel flow (Q) of the aircraft. The final set of equations are given hereafter:

$$\dot{\gamma} = \frac{L + T \cdot \sin\alpha}{m \cdot V} \cdot \cos\varphi - \frac{g}{V} \cdot \cos\gamma \qquad (2.1)$$

$$\dot{V} = \frac{T \cdot \cos\alpha - D}{m} - g \cdot \sin\gamma \qquad (2.2)$$

$$\dot{h} = V \cdot \sin\gamma \qquad (2.3)$$

$$\dot{\varphi} = p \qquad (2.4)$$

$$\dot{\psi} = \frac{g \cdot \tan\varphi}{V} \qquad (2.5)$$

$$\dot{x}_{east} = V \cdot \cos\gamma \cdot \cos\psi - V_{wind} \cdot \cos\chi_{wind} \qquad (2.6)$$

$$\dot{x}_{north} = V \cdot \cos\gamma \cdot \sin\psi - V_{wind} \cdot \sin\chi_{wind} \qquad (2.7)$$

$$\dot{m} = -Q \qquad (2.8)$$

Here, D is the drag, T the engine thrust, α angle of attack, χ_{wind} and V_{wind} are the wind direction and speed, L is the lift, p is the roll rate and g is gravity.

A normal flight regime, is considered in this study, therefore α is relatively small, and in (2.2) $\cos\alpha$ can be approximated to 1. Further, in (2.1), the term $T \cdot \sin\alpha$ can be considered as negligible in comparison with the lift contribution. This simplifies (2.1) and (2.2) to:

$$\dot{\gamma} = \frac{L}{m \cdot V} \cdot \cos\varphi - \frac{g}{V} \cdot \cos\gamma \qquad (2.9)$$

$$\dot{V} = \frac{T - D}{m} - g \cdot \sin\gamma \qquad (2.10)$$

The differential equations (2.3) to (2.10) constitute then the basic equations of motion of the aircraft model. The aerodynamic forces are modelled using an estimate of the aircraft trimmed aircraft polar, with an extension to take into account the effects of Mach-drag rise. The Mach-drag rise component is usually a function of Mach number and lift coefficient. A 2-dimensional look-up table is used to model the aircraft polar.

The thrust is computed from a given thrust over weight ratio for a given aircraft, by multiplying this ratio by a percentage thrust command and the maximum take-off mass of the aircraft type at hand. The thrust over weight ratio is calculated from a two-dimensional look-up table, as function of Mach and pressure altitude. The thrust characteristics used in the model are typical for high by-pass turbofan aircraft. Due to the fact that the thrust is calculated as a dimensionless thrust over weight ratio, the thrust model can be adapted easily to various aircraft types, without significant changes to the thrust model. By using a calibration factor (ranging from plus or minus 20%) the model can therefore easily be adapted to any aircraft type.

The autopilot allows the aircraft to follow the reference targets (desired airspeed and altitude). The principle used to design the autopilot is based on the total energy [4][7]. It is beyond the scope of the present paper to go into the details of the actual implementation of the controller. The tuning of the parameters of the pilot model and the validation of the overall resulting trajectories has been performed using two references: a fixed base cockpit simulator at the Eurocontrol Experimental Centre, based on a high fidelity 6 degree of freedom B747 and A320 aircraft models, and at the National Aerospace Laboratory of Netherlands a high fidelity 6 degree of freedom Fokker 100 simulator.