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CALIBRATION OF AIR COMBAT SIMULATION MODELS BASED ON PERFORMANCE DATA

Jaakko Hoffren and Jari Vilenius

Laboratory of Aerodynamics
Helsinki University of Technology
FIN-02015 HUT, Finland

Abstract

The modelling of high-performance aircraft for air combat simulations has been studied in order to investigate whether a realistic model can be obtained by calibrating a crude basic model by performance data. Simple correction functions of one variable are developed for the thrust and drag using two steady-state performance points, assumed to be known. Test calculations are performed to compare the steady-state performance predictions and simulated dynamic maneuvers given by an uncalibrated and a calibrated model with available reference data. The calibration is found to improve the prediction accuracy, but the simple procedure is of somewhat limited power and sensitive to the data points available.

Introduction

Air combat simulations can be applied, among other purposes, to develop efficient tactics against perceived threats. The studies require that representative numerical models of the aircraft involved are available. Often, however, such information related to foreign equipment is inaccessible, and models must be created based on scarce data. Owing to the problem set-up, only performance models, containing thrust and drag arrays in different conditions in the flight envelope as their main elements, can be considered.

There are numerous ways of varying complexity to estimate the thrust and drag of an aircraft that is only superficially known. For example, the drag polar can be calculated applying DATCOM[1] or by extensive Navier-Stokes computations. Because the performance of an aircraft depends critically on the difference between thrust and drag, it appears that pure, separate thrust and drag calculations cannot give reliable performance predictions, even if the most sophisticated methods are applied.

On the other hand, it can be considered that often some performance figures of the aircraft under study are available. If the estimated model is reasonable with correct qualitative dependencies on Mach number, altitude and angle of attack, the fidelity of the model may be significantly improved by a calibration based on scarce performance data. In such a case, the enforcement of modelled thrust and drag to match each other in few steady-state performance points leads to a model correction in the whole flight envelope.

In this paper, the potential of aircraft model calibration by performance data is studied. For test calculations, a simple calibration method suitable for high-performance aircraft is devised. The improvements in the performance predictions obtained with few calibration points are demonstrated as comparisons of steady-state performance indicators, and the practical impact of the enhanced model fidelity is assessed via prescribed dynamic maneuver calculations and by actual air combat simulations. Based on the observations, the feasibility of the present calibration approach is assessed.

Aircraft Modelling

The performance models considered here contain numerical data arrays for the maximum and idle thrust, drag and maneuvering limits, like the maximum roll rate. An important single parameter is aircraft weight, which must be correct within a few per cent to be representative. Only thrust and drag modelling are relevant in this context, and they are briefly discussed in the following.

Estimation of Thrust

In the high-performance aircraft model considered, the maximum thrust with and without reheat are defined as two-dimensional arrays depending on altitude and Mach number, covering the whole flight envelope. Only the steady-state operation is modelled.

The selected thrust estimation method uses a PC code, called GASTURG.[2] The code contains analytical

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thermodynamic models for engine components, the operation of which is balanced at each operating point to yield the overall performance parameters of the engine. The code can model specific types of gas turbines, like a twin-spool turbofan with reheat, and the installation effects can be taken into account by an intake efficiency module. In the component models, various losses can be taken into account, and internal bleeds are included. The operation of the engine can be studied in different ambient conditions, and several operating limits can be set. Thus, it is considered that the calculation method itself is fairly sophisticated.

In modelling a poorly known engine, the uncertainties lie in the estimation of input data for GASTURB. Primary variables for an installed gas turbine model that should be representative are at least the inlet efficiency, mass flow, bypass ratio, overall pressure ratio, turbine inlet temperature and reheat temperature. Typically, all of these are not known but they must be guessed, based on general knowledge of relevant reference engines. Without any guidance, success is unlikely. However, the approach becomes feasible if thrust at a single operation point is known, as assumed here.

The known maximum thrust values that serve as a basis for the engine model are often related to an uninstalled engine in a test bench in ISA, sea-level conditions. In the first phase of modelling, the uncertain primary engine parameters are iteratively and reasonably varied so that GASTURB predicts the correct thrust with and without reheat. As the second, relatively straightforward phase, the maximum thrusts for an installed engine are extrapolated into the flight envelope while maintaining the operating parameters within allowable limits. The limits for each engine, however, depend on its control system, and they are not trivially guessed accurately.

As evident from the above, the thrust estimates extrapolated from a single point outside the flight envelope cannot be very reliable quantitatively. However, because gas turbines operate generally in a well predictable manner in different ambient conditions, the models should predict qualitatively correct trends with respect to altitude and Mach number. This model property appears to make the calibration a feasible idea.

Estimation of Drag

In the aircraft model under study, the drag coefficient is expressed as a two-dimensional numerical array depending on the lift coefficient and Mach number in the complete operating range. Although noticeable, Reynolds number effects coupled to altitude are ignored, as are the variations with center of gravity. These simplifications alone restrict the achievable accuracy of the model, making the drag modelling and calibration tasks somewhat easier. Because of the initial assumption of only superficial knowledge of the geometry of the aircraft to be modelled, only simple drag prediction methods are to be considered.

The drag coefficient estimation is divided here into subtasks. The main division runs between zero-lift and lift-dependent drag, which are dealt with separately by different approaches. For high-performance aircraft, the zero-lift drag is essentially the minimum drag at each Mach number, and the assumption of a symmetrical polar is reasonable. Another division according to the applied methods is made into the subsonic and supersonic region.

For the zero-lift drag estimation, the DATCOM method[1] is heavily utilized. In this approach, the aircraft is divided into simplified wing-like or fuselage-like components whose drag is separately calculated using simple, semi-empirical formulas. As the input variables, general geometrical parameters like wetted area, fineness or thickness ratio, sweep angle and leading edge radius as well as a representative Reynolds number are required. The form and friction drags as well as the supersonic wave drag of the components are eventually summed up for the total drag that can be modified with an interference factor. In addition to DATCOM, some component drags are evaluated based on Raymer,[3] and the intake spillage drag estimate relies on a procedure described in Ref. 4. Here, the engine mass flow values from the GASTURB calculations are required, adding to the uncertainties involved. The most sophisticated method in the drag prediction is applied to the wave drag of the fuselage that is computed using a full-potential-based code RAXBOD[5] where the fuselage is treated as an axisymmetric body. The methods described give meaningful results only in subsonic and supersonic ranges. The problematic transonic range is covered by manual interpolation based on empirical knowledge of the drag rise behaviour.

The lift-dependent drag is estimated entirely based on empirical data of a few known reference aircraft. Calculations appear unpractical because of a few strong factors: Simple division into components is not realistic for current fighter configurations, necessitating the use of complex methods; no calculation method works reliably at high lift coefficients that must be covered here; and the flight control systems modify the aircraft configurations in a generally unknown manner. The approach adopted here is based on empirical, lift-coefficient-dependent estimates for the Oswald factor $e(C_L)$ defined as

$$e(C_L) = \frac{\Delta C_L^2}{\pi A \Delta C_{Di}} \tag{1}$$

where ΔC_L is the lift coefficient increment related to a drag coefficient increase ΔC_{Di} at the lift coefficient C_L in question and A is the wing aspect ratio. For configurations of each aircraft generation that resemble each other, the Oswald factors are assumed to be the same in a few limited lift coefficient ranges. In the subsonic region, the applied Oswald factors are assumed to be constants, but in the supersonic zone, they depend on the Mach number.

Clearly, the drag estimation by the crude methods described above cannot be reliable. The accuracy of individual polar points is expected to be not much better than 20 per cent, which is clearly too poor for reasonable performance predictions. However, like the thrust estimate, the drag array can be thought to model a realistic, physically sound qualitative dependence on its parameters. This assessment is essential for the success of a simple model calibration.

Model Calibration

General Principles

The model calibration here means that the performance predictions obtained with the model are matched to some known point performance values, on the basis of which the model thrust and drag arrays are corrected in the whole flight envelope.

To be general and practical, the calibration method must be based on few, well-definable performance points. Beside the performance values themselves, the ambient conditions and aircraft configuration must be accurately known at these points to enable model improvement. A calibration method developed on the basis of scarce data must also be simple and behave smoothly so that it can be applicable to different aircraft types. In addition, the calibration may not distort the qualitative behaviour of the model.

For the calibration, such performance points that describe the fundamental aircraft characteristics as well as possible should be chosen. They should also relate to situations, from which one can assume to get useful data. Bearing in mind the air combat simulation applications, suitable calibration points are related to sustained turn performance and maximum speed.

In this work, it is assumed that just two calibration points are available. The first one is a sustained level turn using maximum afterburner at a subsonic speed at low altitude. Such a maneuver is representative of close-in combat, and the data may be available, for example, from an air show display. The second point is the supersonic maximum level speed at the tropopause. This value, important for beyond-visual-range combat, is often fairly well known for each aircraft of interest. However, the calibration method devised is not specifically related to these points; any point with sufficient data will do.

Calibration functions

At the turn point, at least two of the quantities of turn rate $\dot{\Psi}$, true airspeed V, bank angle ϕ and turn radius r must be known. The ambient pressure altitude and temperature must also be available to determine the density ρ and Mach number in addition to the aircraft mass m and external store configuration. When the necessary data is gathered, the aircraft lift coefficient is calculated from

$$C_L = \frac{mg}{0.5\rho V^2 S cos\phi} \qquad (2)$$

where S is the chosen reference area. In a level turn, the relations

$$tan\phi = \frac{V\dot{\Psi}}{g} = \frac{V^2}{gr} \qquad (3)$$

are available for the determination of necessary input for Eq. (2).

In the next phase, the drag predicted by the uncalibrated model D_{pred_1} in the corresponding configuration is calculated using the known C_L and Mach number. Also the thrust estimate T_{pred_1} is calculated by GASTURB at the correct Mach number, pressure altitude and ambient temperature. Because in reality the forces should cancel each other, they are fixed to the value

$$T_{fix_1} = D_{fix_1} = aT_{pred_1} + (1-a)D_{pred_1} \qquad (4)$$

where the weighting factor a is chosen to reflect the assumed mutual reliability of the thrust and drag estimates. Thus, at the calibration point, the thrust correction factor is T_{fix_1}/T_{pred_1} and the drag coefficient correction factor is D_{fix_1}/D_{pred_1}.

Correspondingly, at the maximum speed point, the lift coefficient is determined from Eq. (2) with $\phi = 0$, and the estimated thrust and drag are calculated. From the condition of force equilibrium, the second correction factors T_{fix_2}/T_{pred_2} and D_{fix_2}/D_{pred_2} are obtained.

The problem of the calibration lies in the generalization of the corrections into the whole flight envelope. In general, it can be assumed that the thrust and drag coefficient inaccuracies and the necessary corrections are primarily functions of the same parameters as the quantities themselves, formally expressed as $T_{corr}/T_{pred}(H, Ma)$ and $C_{D corr}/C_{D pred}(C_L, Ma)$. If several calibration points were available, smooth correction factor surfaces could be adapted to them. However, with just two points in hand, an even simpler approach using a single variable must be taken. After trials, it was decided to apply the thrust correction factor as a function of the equivalent airspeed and the drag correction factor as a function of lift coefficient. With these definitions, the absolute corrections depend on the primary array arguments in a reasonable, smooth way.

Since it is assumed that the thrust estimate is accurate in static conditions, no corrections are applied at zero airspeed. Two different calibration functions are considered. The first one consists of two linear ranges. Below the lower equivalent airspeed EAS of the calibration points, the thrust correction function is

$$\frac{T_{corr}}{T_{pred}}(EAS)_{lo} = 1 + \frac{T_{fix_1}/T_{pred_1} - 1}{EAS_1} EAS \quad (5)$$

In this equation, the turn point is assumed to have the lower EAS. Above this speed, the correction is

$$\frac{T_{corr}}{T_{pred}}(EAS)_{hi} = T_{fix_1}/T_{pred_1}$$

$$+\frac{T_{fix_2}/T_{pred_2} - T_{fix_1}/T_{pred_1}}{EAS_2 - EAS_1} EAS \quad (6)$$

In the second function, a parabola is fitted through the three known points, and the correction is of the form

$$\frac{T_{corr}}{T_{pred}}(EAS)_2 = 1 + A \times EAS + B \times EAS^2 \quad (7)$$

where the coefficients A and B follow from the curve fit. The parabola facilitates an extrapolation at low speeds and a smooth behaviour, but may lead to excessive corrections. To prevent excessive extrapolations at higher equivalent airspeeds than EAS_2, the correction is additionally limited to remain within two per cent of T_{fix_2}/T_{pred_2} with both functions. For the drag, a single function

$$\frac{C_{D corr}}{C_{D pred}}(C_L) = D_{fix_1}/D_{pred_1}$$

$$+\frac{D_{fix_2}/D_{pred_2} - D_{fix_1}/D_{pred_1}}{C_{L2} - C_{L1}} C_L \quad (8)$$

is applied in the whole flight envelope. As a sanity assurance, the correction is limited to lie between 0.8 and 1.3 to prevent possible unrealistic corrections from being used at extreme lift coefficients. The functions are coded in a program that reads the original data arrays and writes the corrected array in the same format.

It is not claimed that the chosen functions are the best possible alternatives, but they represent a reasonable first-order engineering approach to the problem under study. Via an extensive test campaign with numerous aircraft, better functions that are especially suitable for the applied aircraft-modelling methods could probably be found.

Test Calculations

Aircraft Model

For the test aircraft discussed here, the F-16 was used because reasonable published data were available. In the configuration studied, the aicraft weighs 11 metric tons, and only wing-tip missiles are carried as external stores. For the aircraft, a performance model was built applying the methods described in this paper. The external geometry of the aircraft used in the drag prediction was taken from Jane's [6] and other general publications. For the F100-PW-220 engine, Ref. 6 gives relatively detailed information, facilitating a reasonable thrust estimation. In addition to the sea-level static test-bench thrusts, the engine configuration, maximum turbine inlet temperature, overall pressure ratio and bypass ratio are published. Because of the amount of available public data, the basic model should be relatively representative without large errors.

Steady-State Performance

Two point performance indicators were studied in the whole steady-state flight envelope defined by the altitude H and Mach number. The first one is the specific excess power SEP defined as

$$SEP = \frac{T_{maxAB} - D(n_z = 1)}{W} V \quad (9)$$

where T_{maxAB} is the thrust at maximum afterburner, $D(n_z = 1)$ is the drag evaluated at a C_L corresponding to load factor $n_z = 1$, W is the aircraft weight and V the true airspeed. This quantity determines the climb and acceleration potential of an aircraft, thus being an important figure of merit for a fighter. The other performance indicator, directly related to the maneuverability, is the sustained load factor n_{zs} in a level turn, evaluated as

$$n_{zs} = \frac{L(D = T_{maxAB})}{W} \quad (10)$$

where the lift L corresponds to a drag balanced by the maximum-afterburner thrust. All the following studies relate to the standard atmospheric conditions (ISA), where the performance was evaluated by a purpose-built code.

The SEP and n_{zs} values obtained with the uncalibrated model are compared with the reference data in Figs. 1 and 2. With respect to the SEP, the model is optimistic at low to medium equivalent airspeeds and very pessimistic at high speeds, especially at medium altitudes. Concerning the sustained load factor, the errors are qualitatively similar, except an additional pessimistic region at high subsonic speeds. Although the general agreement is reasonable, the accuracy of the uncalibrated model is probably not sufficient for realistic air combat simulations.

In the first calibration test, it is assumed that the actual sustained turn performance is known at sea level at the Mach number of 0.6. In addition, the maximum level speed corresponding to the Mach number of about 1.9

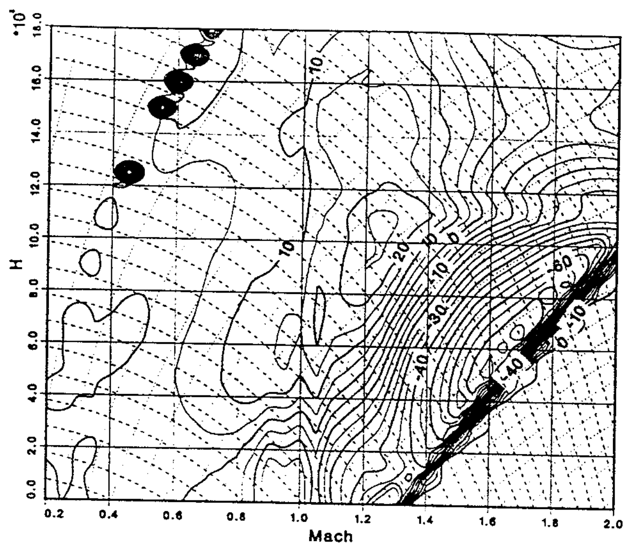

FIGURE 1 - Contours of the SEP difference in meters per second between predictions of the uncalibrated model and reference data. The dotted lines mean constant equivalent airspeeds and the dashed lines constant energy altitudes.

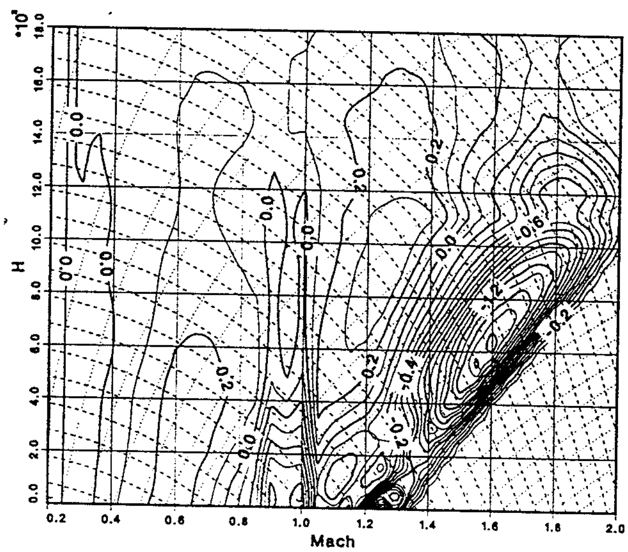

FIGURE 2 - Contours of the difference in sustained load factor between predictions of the uncalibrated model and reference data.

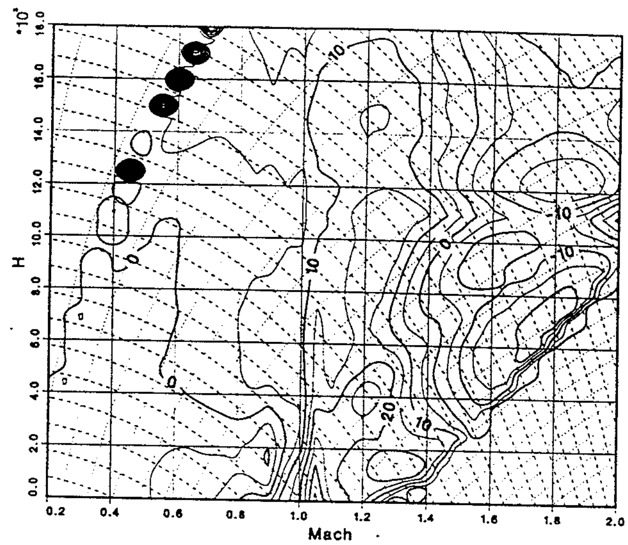

FIGURE 3 - Contours of the SEP difference in meters per second between predictions of the calibrated model and reference data. The turn calibration point corresponds to $H = 0$, $Ma = 0.6$.

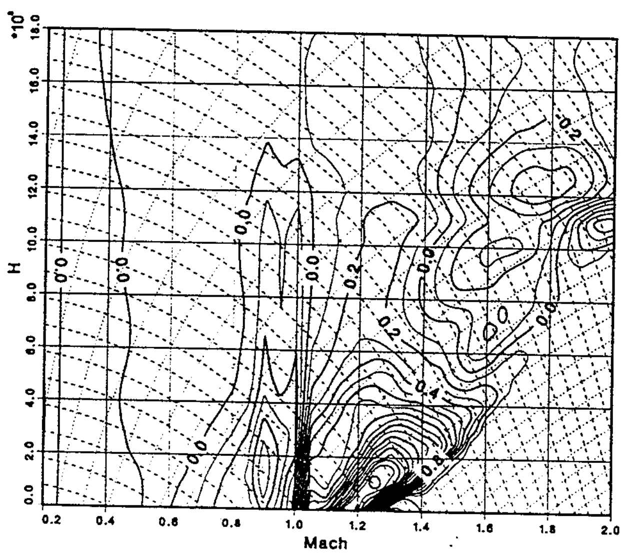

FIGURE 4 - Contours of the difference in sustained load factor between predictions of the calibrated model and reference data. The turn calibration point corresponds to $H = 0$, $Ma = 0.6$.

at H=11 km (tropopause) is also taken as a calibration point. The calibration based on these points reduces the thrust estimate and increases the drag estimate by about 4 per cent at the turn point and increases the thrust and reduces the drag by about 4 per cent at the maximum speed point if the weighting factor a in Eq. (4) is set to 0.5. The resulting SEP and n_{zs} error plots obtained by applying the parabolic thrust correction are shown as Figs. 3 and 4. By comparing them with Figs. 1 and 2 it is seen that the model accuracy is significantly improved. At subsonic speeds, the SEP errors with the calibrated model are less than 10 m/s, and at high supersonic speeds, the errors are again small. At low supersonic speeds, the errors are at their worst, the maximum being about 25 m/s. With respect to the load factor, the errors with the calibration at subsonic speeds are quite small, and in the supersonic region, the remaining errors are important only at low altitudes. Clearly, this calibration shows the potential of the method.

To study the sensibility of the calibration to the performance points applied, another calibration was performed. In this second case, the maximum speed point was left unchanged, but the Mach number of the turn point was increased to 0.8. At this point, the calibration increased the thrust and decreased the drag by about 1 per cent instead of opposite corrections in the first case. The error plots obtained again with the parabolic thrust calibration are shown in Figs. 5 and 6. Although the results changed to some extent, as expected, the overall differences are small. At least with this test data, the calibration appears not to be overly sensitive to the

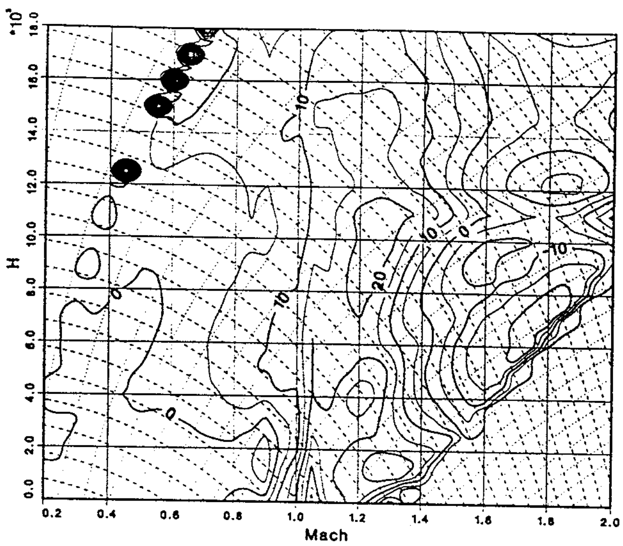

FIGURE 5 - Contours of the *SEP* difference in meters per second between predictions of the calibrated model and reference data. The turn calibration point corresponds to $H = 0$, $Ma = 0.8$.

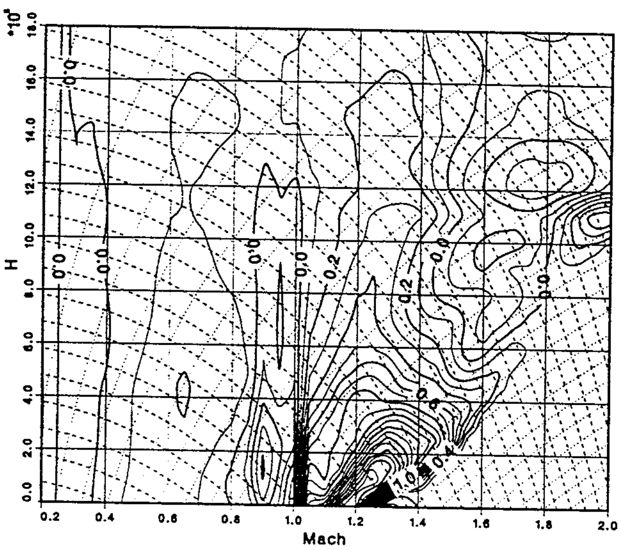

FIGURE 6 - Contours of the difference in sustained load factor between predictions of the calibrated model and reference data. The turn calibration point corresponds to $H = 0$, $Ma = 0.8$.

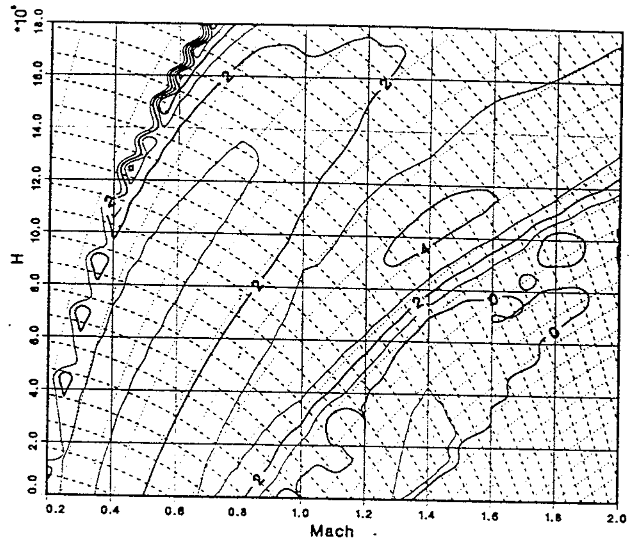

FIGURE 7 - Contours of the *SEP* difference in meters per second between predictions of the model calibrated using two different turn data points, when the parabolic thrust correction function is applied.

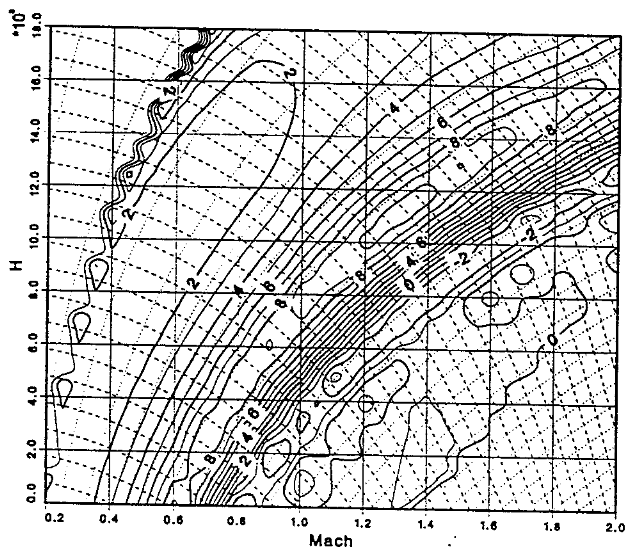

FIGURE 8 - Contours of the difference in sustained load factor between predictions of the model calibrated using two different turn data points, when the piecewise linear thrust correction function is applied.

exact location of the calibration points.

Another sensitivity test concerns the thrust correction functions. With the piecewise linear corrections, the results are essentially similar to the ones presented above using the Ma=0.6 point as a calibration point. However, if the Ma=0.8 point is used, the results with the linear thrust correction deteriorate noticeably, making it more sensitive to the available data. The effects are illustrated in Figs. 7 and 8 comparing the differences in *SEP* predictions using the two calibration points.

Based on the steady-state performance calculations, it appears that the calibration can improve the accuracy of an aircraft model markedly. If the corrections at the calibration points are small, just a few per cent, the parabolic thrust correction is better than the linear one. However, if large corrections are necessary, the more robust linear function is safer. The calibration with scarce data is bound to be sensitive to the data available to some extent, but it will certainly remove possible gross errors that may exist in a model put together by the simple methods considered here. These conclusions are backed by some additional calculations with two other aircraft types, the results for which cannot be published.

Air Combat Maneuvers

Although the calibration improves the accuracy of the performance predictions, it is not clear how meaningfull this improvement is in an actual air combat simulation. In principle, the issue could be clarified by 1 vs. 1 simulations where the reference aircraft would be separately set against an uncalibrated and a calibrated model aircraft. To give statistically representative results in such complex multi-disciplinary situations, however, an exhaustive test program involving numerous different initial conditions would be needed. Because of the practical constraints, a simplified and more directly controlled approach is taken here, where a set of predetermined combat-related maneuvers selected using Ref. 7 are studied to compare the predicted flight paths and state variables. In addition, limited air combat simulations are also performed to support the conclusions.

For the computational tool, an updated version of the published AML-75 air combat simulator [8,9] was applied. It can simulate 1 vs. 1 close-in combat, where the maneuver decisions at predetermined intervals are made by evaluating a few trial maneuvers based on a group of simple criteria for the tactical situation. Although the basic code is old, the fidelity of its aircraft modelling essentially corresponds to the current version of the AML family. To improve its flexibility, the code was modified to read different aircraft data files, and a section to define the desired control commands was included. In addition, the original, non-physical two-mode flight path integration of AML-75 was replaced by a continuous scheme that treats attitude changes with reasonable single-degree-of-freedom dynamics. Test runs have shown that the updated code offers a greatly enhanced realism that probably exceeds the level of latest commercial performance-model-based AML's.

For the tests, nine different dynamic maneuvers initiated in level flight at 5000 meters were studied, and the situations were followed typically for one minute. The maneuver set consisted of different level turns, a half-roll/half-loop direction change, flat scissors, rolling scissors, a defensive spiral and a sharp turn initiation [7].

As an example of the results obtained, Figs. 9 to 11 show qualitatively the flight paths and some main state variables in a fast level turn applying maximum thrust. The turn is intiated from a level flight, and a load factor of 6.5 is maintained until the maximum lift becomes the limiting factor. The maneuver is terminated after a 360° turn. From Figs. 9 to 11 it is seen that the calibration improves the agreement with the reference results. However, in this maneuver at a high lift coefficient, the correction is excessive, which is an expected result based on Eq. (8) and the drag corrections at the calibration points. At lower lift coefficients between the calibration point values, the accuracy improvement resulting from the calibration is generally somewhat better. To obtain some perspective of the errors in the flight path predictions, the results shown here correspond to an aircraft's weight variations of less than 5 per cent, as noted in the sensitivity study of Ref. 10.

a)

b)

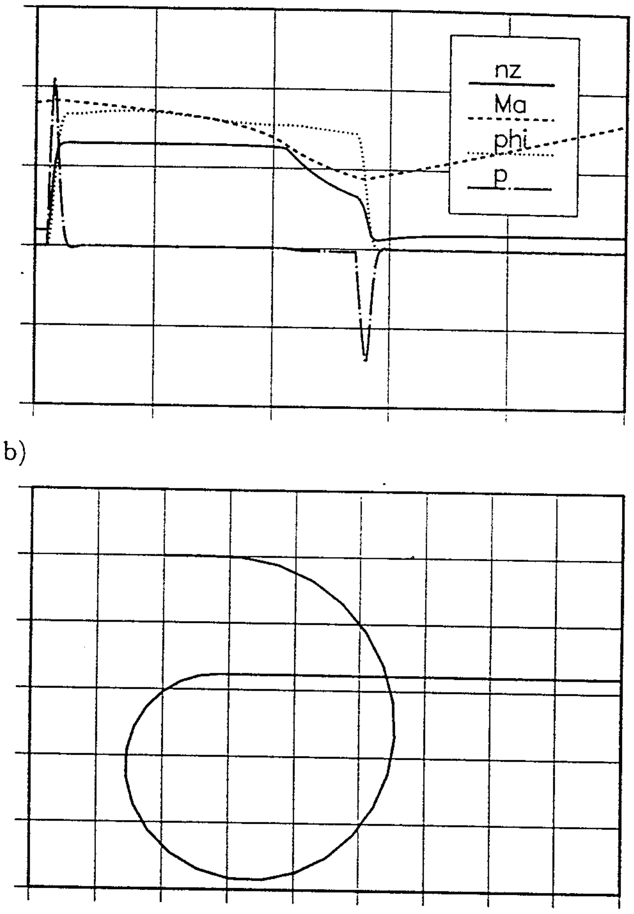

FIGURE 9 a) Load factor n_z, Mach number Ma, bank angle *phi* and roll rate p as functions of time b) flight path in a level turn obtained using the reference data, when the load factor is 6.5 or limited by the maximum lift.

The limited air combat simulations gave results that support the cautious optimism about the usefulness of the calibration. An example of the tests made is shown in Figs. 12-14, where an initially symmetric 1 vs. 1 situation is studied. With reference aircraft data for both combatants and a deterministic decision logic, the resulting flight paths should be symmetrical, as is the case in Fig. 12. When the aircraft characteristics are changed, the situation becomes asymmetric, and a figure of merit in the comparison of Figs 13 and 14 is their resemblance to the symmetrical reference case. With one of the reference aircraft models replaced by the uncalibrated model, the flight paths quickly deviate from symmetry in Fig. 13. Instead, when a model calibrated as earlier is pitched against the reference aircraft, the resulting maneuvers remain much more symmetric for some time, as seen in Fig. 14. However, it must be stressed that the general impact of the calibration on the fidelity of air combat simulations could not be established in this work and remains to be seen as experience builds up.

a)

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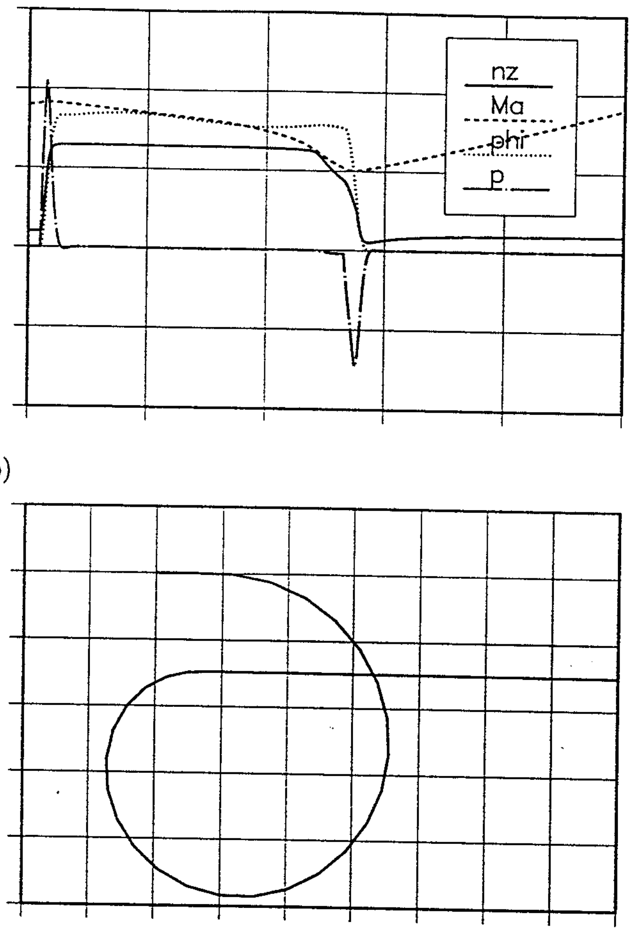

FIGURE 10 a) Load factor n_z, Mach number Ma, bank angle phi and roll rate p as functions of time b) flight path in a level turn obtained using the uncalibrated model, when the load factor is 6.5 or limited by the maximum lift.

a)

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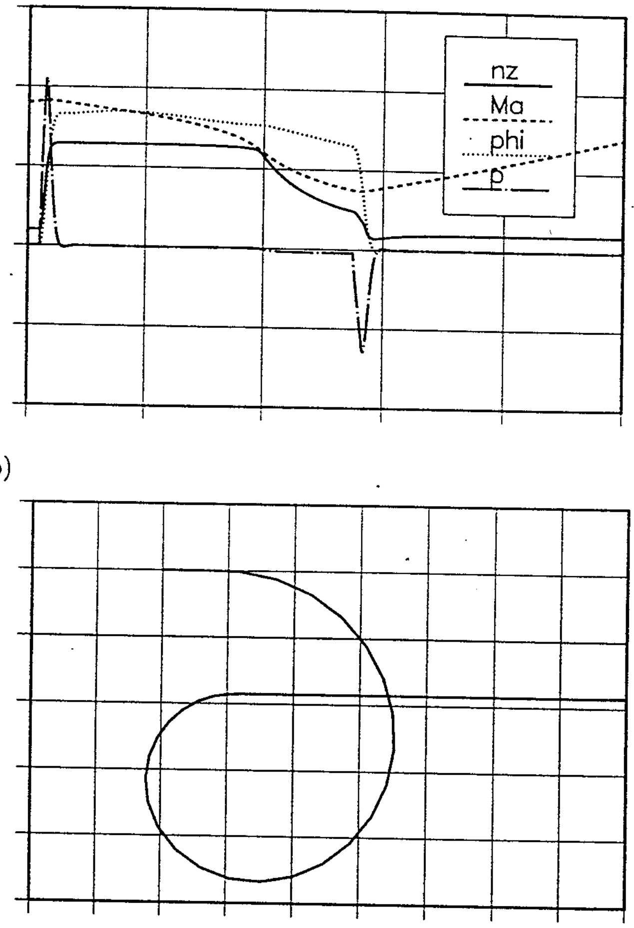

FIGURE 11 a) Load factor n_z, Mach number Ma, bank angle phi and roll rate p as functions of time b) flight path in a level turn obtained using the model calibrated by the parabolic thrust correction and Ma=0.6 turn point, when the load factor is 6.5 or limited by the maximum lift.

Conclusions

The modelling of high-performance aircraft for air combat simulations was studied. The purpose was to investigate if a realistic model can be obtained by calibrating a crude basic model by scarce performance data. It was assumed that, for the basic model, only the external geometry of the aircraft under study is roughly known in addition to some information about its engines. Consequently, the adopted modelling methods are simple and inaccurate.

For the calibration, two steady-state performance points were assumed to be available. Based on the force equilibrium in those points, simple correction functions of one variable were developed for the thrust and drag.

Test calculations were performed to compare the steady-state performance predictions of an uncalibrated and a calibrated model with available reference data. It was noted that the calibration has potential to improve the prediction accuracy, but with few data points, the calibration is bound to be of limited power and somewhat sensitive to the data points available. Additional tests with predetermined maneuvers confirmed the improved realism by calibration in dynamic situations, and initial air combat simulations supported the conclusions.

It appears that the procedure described may become a practical way of creating threat models for air combat simulations. However, only future experience will reveal if the results obtained through applying it are realistic enough to be practical and if suitable performance data for the aircraft of interest can be found.

Acknowledgement

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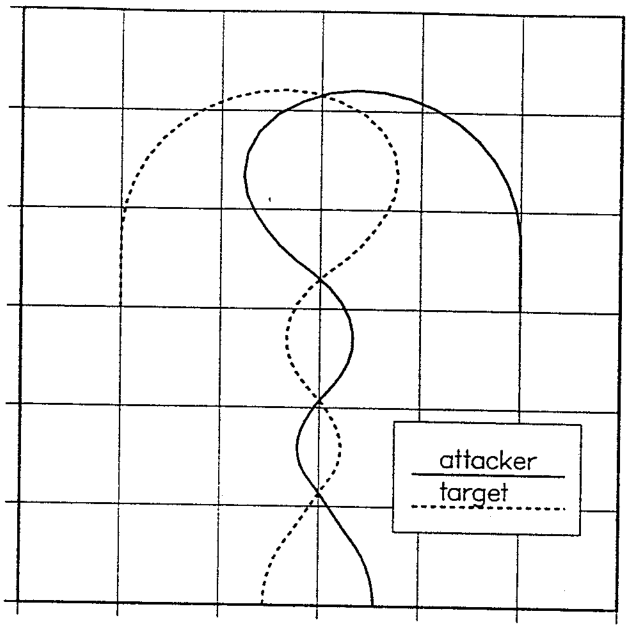

FIGURE 12 - Horizontal flight path projections in an air combat simulation initiated symmetrically at $Ma = 0.8$, $H = 5000m$ using reference data for both aircraft.

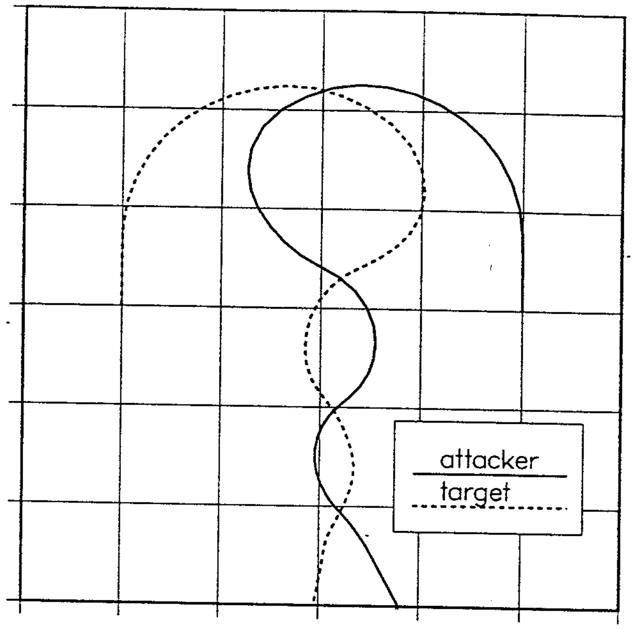

FIGURE 14 - Horizontal flight path projections in an air combat simulation initiated symmetrically at $Ma = 0.8$, $H = 5000m$ using reference data for the attacker and a calibrated model for the target.

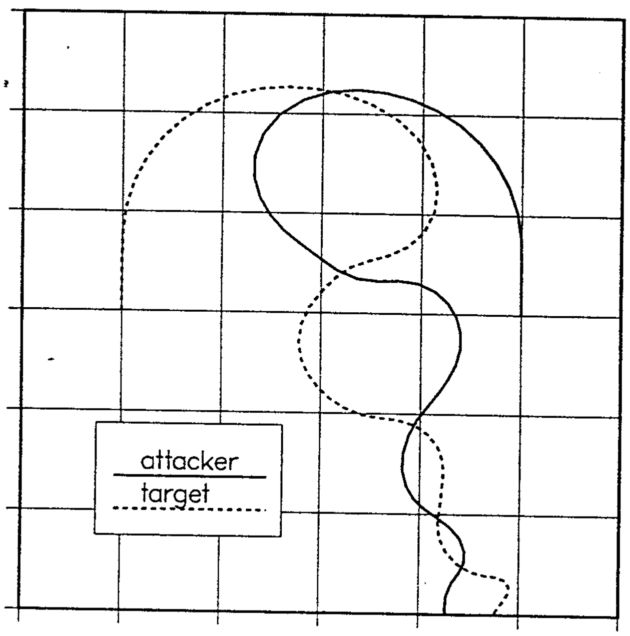

FIGURE 13 - Horizontal flight path projections in an air combat simulation initiated symmetrically at $Ma = 0.8$, $H = 5000m$ using reference data for the attacker and the uncalibrated model for the target.

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