CONCEPTUAL AIRCRAFT DESIGN MODEL MANAGEMENT DEMONSTRATED ON A 4TH GENERATION FIGHTER

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Abstract

Model management during conceptual aircraft design is an important issue. This paper shows the basic ideas and capabilities of the conceptual aircraft design framework developed at Linköping University with focus on efficient low fidelity geometry definition. As an example, the analysis of an F-16 fighter is presented.

1 Introduction

With the F-16 as one of the best researched 4th generation fighters with a lot of available publications, the Lockheed Martin F-16 "Fighting Falcon" was chosen for a thorough conceptual design framework analysis. The framework benchmark in this paper is related on two topics, the aircraft performance analysis and the framework capability regarding model management and data structure efficiency.

The conceptual aircraft design framework is developed at Linköping University within a national aviation research project (NFFP) started in 2009; development is still ongoing. Even though parts of this framework has been thoroughly tested and fine-tuned during development, this F-16 design case is the first overall analysis of this framework.

2 Methodology and Implementation

2.1 Conceptual aircraft design strategies

During the design process from conceptual to preliminary and finally to detail design, a stepless transition and non-dissipative information flow is desirable. For initial design, two approaches are common, the classical aircraft preliminary sizing (as in [1] or a "match design" approach e.g. supported by the open vehicle sketch pad (openVSP) from NASA [2]. The former is a requirement driven clean sheet design approach whereas the later is similar to a classical reengineering approach (as used in this paper). In common with both approaches is the absence of crucial parameters (airfoil data, wing twist) in the initial assessment. However, during the classical sizing approach with its empirical equations (e.g. in [3]), a huge number of (unknown) parameters are implicitly included in the concept analysis. These implicit parameters -invisible included in the formulas by the creation process, mainly based on statistic data- are not explicitly known and not traceable. This issue leads to the common practice during classic preliminary sizing to apply correction factors in the analysis wherever a positive or negative deviation of the design compared with the statistical base is expected.

2.2 Fidelity level versus data complexity

This classic aircraft sizing process can be seen as a (statistical) knowledge-based engineering approach (KBE) with a small amount of explicit defined parameters (the basic characteristics) analyzed with respect to a large quantity of statistic data. Hahn [4] calls this a reduced order model (ROM) which represents a regression of the "real" data setup. Because of the preliminary design process is a balance between complexity (number of parameters) , productivity (number of concepts) and costs (usage of infrastructure), this basic ROM approach supports a very good fidelity compared to the less project specific input data.

However, adding stepless information to the project is a delicate problem, because of the nature of the basic sizing functions with its unknown blurred parameters inside. This problem is well known from systems engineering and simulation during the transition from empirical formulas towards component based higher fidelity calculations.

This "fidelity gap" is especially present on aerodynamics: The basic aerodynamic concept is sufficiently captured by low/medium fidelity (LF/MF) aerodynamic analysis methods. High fidelity analysis, taking into account interference effects, transition points, eventually existent flow separation, trans- and supersonic regions or aero-structure effects require a sufficient modeled geometry which to develop is actually the task during the consecutive work within the preliminary and detail design phase. These analysis methods are usually finite elements methods directly related to the 3D-geometry (so no additionally data is assumed during analysis). [5] made a classification approach of the different tools and methods based on the work of [6], shown in Fig. 1.

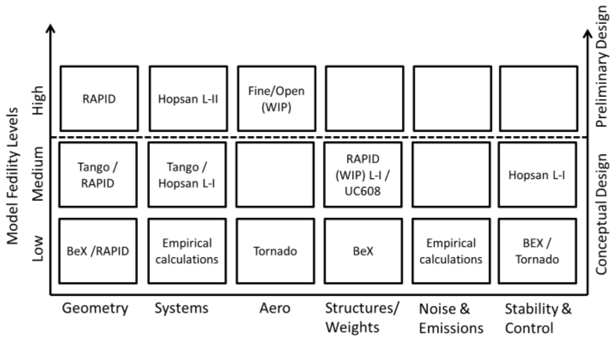


Fig. 1 : Model fidelity level classification of the tools within the framework [5]

An important feature is the feedback of the analysis fidelity and the used input information within the entire tools. Especially during LF mission and performance estimations, some (handbook function based) analysis take only a small subset of the available data into account. This can fool the developer who e.g. already created a complex geometry and assumes that the analysis is performed on the geometry that is rendered in the GUI or the CAD environment.

2.3 The Conceptual Design Framework

The conceptual design framework at Linköping University, presented in [7] is a combination of a flexible, object-oriented interpreter language part (called TANGO) and a matching full 3D CAD part (called RAPID). This combination offers great (user) flexibility and ensures data consistency. Tight integrated are the in-house tools Tornado [8] and Hopsan for LF and MF/HF analysis. Other descriptive design formats (CPACS, openVSP, etc.) can be directly supported by the close integration of the parametric data in XML format.

2.3.1 Framework Architecture and Data Handling

The focus of the framework (development) is on data handling capability, component libraries and analysis capability in order to serve for two main features:

- transition less data growth
- simplicity and robust design space [7]

The first supports a flexible and efficient way of working and the second is a preparation for optimizations as well as to back the user in staying in front of the project; even if many operations can be automated, the user has to hold the control of the project and should not lose the overview.

2.3.2 Tools and Functionality of the Framework

The core frame consists of four parts, namely Tango, RAPID, Tornado and Hopsan, each with a distinct purpose shown in Fig. 2. In order to show the smooth database growth, aircraft modelling was started in Tango with a (low-quality) 3-side drawing of the aircraft geometry only. This approach is explained in the section below.

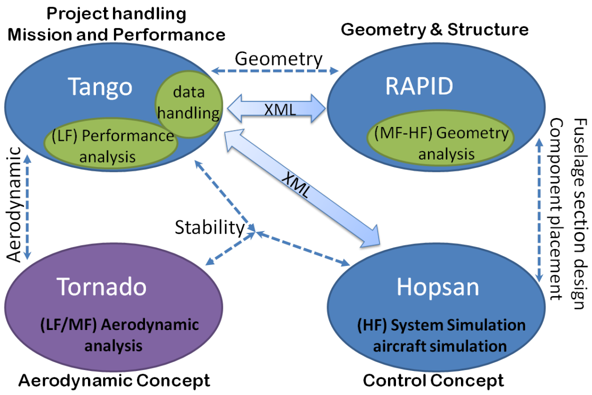


Fig. 2 : Tool functionality split-up within the framework

2.4 Aircraft Modeling

Geometrical data was obtained from an array of different sources [9] [10], including data ripping from published 3-view drawings [11], shown in Fig. 3 together with the sketch of the lifting surfaces.

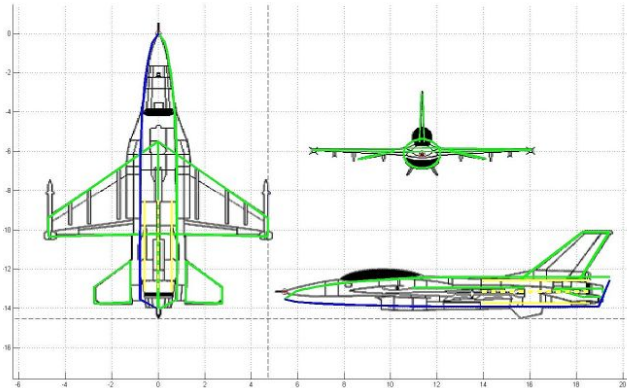


Fig. 3 : 3-side drawing of an F-16 [11] with the overlay of the low-level surface geometry definitions

In this stage, geometric details like the dorsal fin extension of the vertical stabilizer, wing and stabilizer tip shape as well as the fuselage geometry (canopy, air intakes, etc.) are not considered because this first analysis is only intended to catch the aerodynamic concept and serve for a rough analysis of the outline of such an aircraft, known as the sizing process during a (real) bottom up aircraft development process. Further data input is the engine deck data of the F110-132 engine. This data is retrieved by an engine simulation (commercial software GasTurb, based on 0-D modelling technique); this engine model is trimmed towards the few published engine data like bypass and pressure ratio, turbine inlet temperature, size and reference thrust. This complementary engine data replace the default implemented generic (statistical) engine model (see Fig. 4).

When reverse engineering, the global geometry is picked up by the first sketch, several important geometrical features influencing the aerodynamic performance of the aircraft are still unknown. These are e.g. the main wing incidence and twist. Quite often the wing profile and wing profile distribution are also unknown; here, these data is added by the Tornado tool with help of (semi-)automated scripts. With the rough geometry defined, the geometric data is exported to RAPID, a full CAD (CATIA) environment with geometry and structural analysis capability. Here, the fuselage geometry can be modeled more precisely either by:

- reengineering of the geometrical shape (with help of drawings, pictures, etc.)
- development of an requirement driven design by the needed volumes and shapes for engine(installation), ducting, cockpit, payload, fuel system and other on-board systems.

The second option is the same procedure as in a classic aircraft development process after the initial sizing with a highly related KBE approach with a function-mean related implementation (a classical product development method). The focus is hereby mainly related to the cabin layout in civil transportation airplanes and to systems integration in military applications. Even though a central database is used in this framework, the geometry has to be adapted towards the analysis tool's needs (see Fig. 5).

3 Model Analysis

Model analysis is based on the classical conceptual approach -leaping the sizing approach- and starts directly with the iterative penalty factor

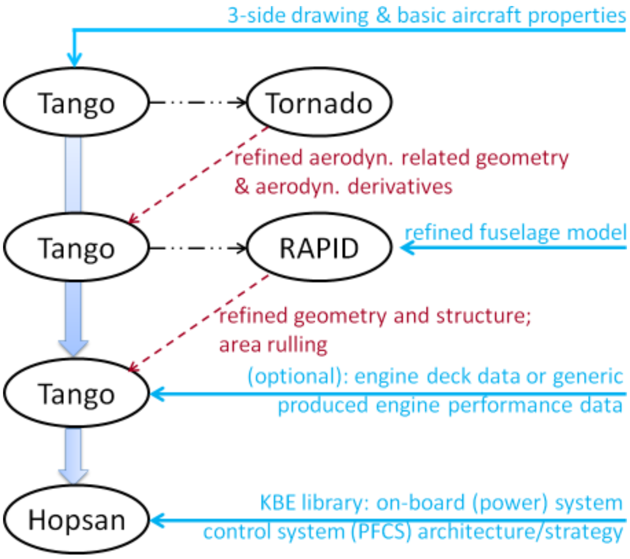


Fig. 4 : User input and tool/analysis data accumulation during the design process

based weight estimation method [12], LF aerodynamic calculations and whole mission simulations.

Geometric adaptations and the aerodynamic coefficients are conducted by a lattice vortex panel method (VLM) for low flight velocities and area ruling for supersonic flight performance. Beside direct feedback of the results, the calculated coefficients are used as inputs for the six degree of freedom (6DoF) simulation model (see Chapter 5). The outcome of this step is validated by experimental data comparison (e.g. with [13])

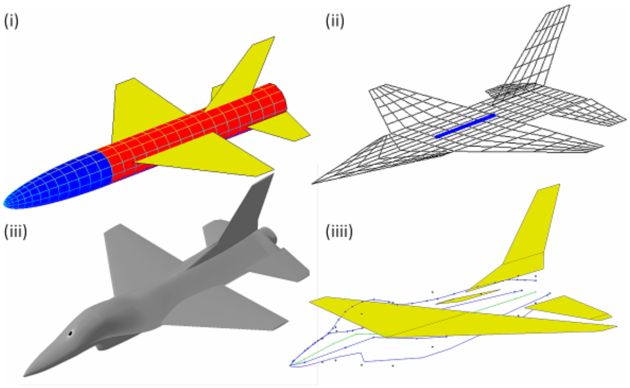


Fig. 5 : Aircraft geometry representation: (i) Tango LF model (used for LF analysis), (ii) Tornado model, (iii) RAPID (CAD) model and (iiii) the CAD model in Tango

3.1 Aerodata and Structure

The aerodynamic modelling of the F-16 model necessary for obtaining an initial estimation of the aerodynamic coefficients was executed in Tornado, a vortex lattice implementation in MATLAB [8]. The aircraft was divided into separate lifting surfaces: nose, fore body, main wing, aft fuselage, taileron and vertical tail. The resulting geometry can be seen in Fig. 6. Wings were assumed to be thin but cambered, the flow inviscous and the angles of attack small. For the F-16 case, the wing profile is known but the wing was nevertheless modeled as a flat plate in the first geometry approximation. The direct influence on the aerodata is that the zero lift pitching moment is too low, and that the main wing incidence will be offset by the zero lift angle of attack.

3.2 Mesh generation

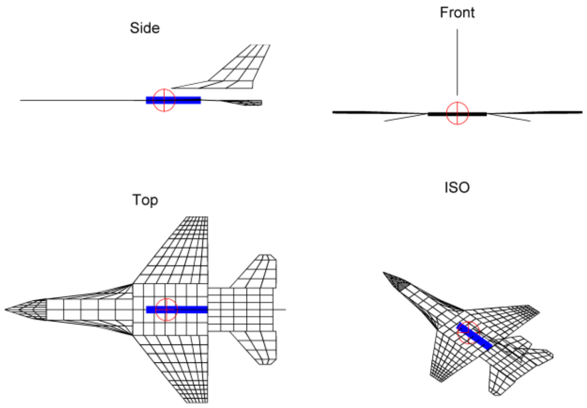


Fig. 6 : Tornado VLM model of the F-16 showing paneling and lifting surface layout, including the mean aerodynamic chord

Tango creates a Tornado compatible input file, including the data needed for mesh generation, from the geometry database. Tornado is then called in batch mode for an automated grid convergence study. By default, the mesh generation data is updated both in the local tornado data and in the master, subject to the outcome of the grid convergence study. The appropriate panel density of the model is determined via a grid convergence study in lift, drag and pitching moment coefficients over the main wing. The mesh resolution was increased in a series of iterations, with the aerodynamic coefficients evaluated at each step. The cutoff level for coefficient change between iterations was set at 2%, which is well within the accuracy of the method. This yielded a total panel count on the main wing of 100 panels. A cutoff level of 1% was tried, but this gave a significant increase in the number of panels. The convergence history can be seen in Fig. 7. The pitching moment coefficient was the last coefficient to converge.

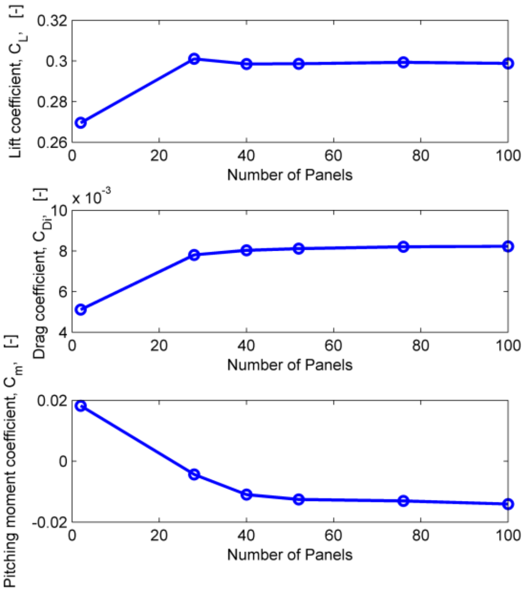


Fig. 7 : Convergence history for the main wing of the F-16 model. The lattice is linearly distributed as no convergence benefit was found using higher order distributions

The produced trimmed polar, shown in Fig. 8, showed a slight difference with flight test data at higher lift coefficients (CL>0.6) [10].

The incidence of the main wing is found by rotating the wing until the target lift coefficient, in this case the cruise lift coefficient of 0.5, was found. This was done while the body angle of attack was kept zero in order to keep the induced drag stemming from the low aspect ratio lifting fuselage low.

The twist of the main wing was found by optimizing the twist distribution to give the best glideslope at target lift coefficient. The optimization was done using a simple gradient based search. These geometrical features are updated in the project database. Once the geometry has been established, Tornado delivers the aerodynamic coefficients and linearized derivatives around a selected mission state; these control power derivatives are needed for preliminary sizing of the control surfaces and associated servos.

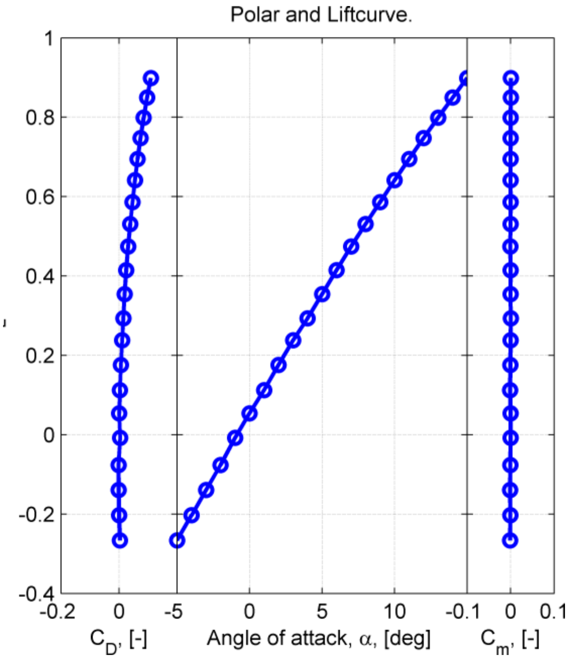


Fig. 8 : Numerical subsonic drag polar for the F-16 model

3.3 Supersonic Drag Estimation

Within RAPID area distribution is estimated using the geometry available for analysis. The two methods that are available are Mach Cone method and Plane Average method. The Plane Average method according to[14] is explained in this section below. For more information on Mach Cone method in RAPID refer [15].

In the F-16 case, areas are divided into two sections: One from nose apex until the inlet position and one from the inlet position to the end of the aircraft. With the intake position and length defined, the number of cross-sections and number of planes in each cross-section can be defined by the user. The intersecting planes are then crated with respect to the flight Mach number. For each plane, intersection area is calculated and

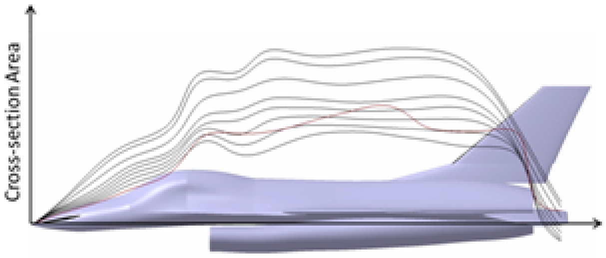


Fig. 9 : Area ruling for different Mach numbers directly analyzed within the CAD environment [14]

all the areas are averaged to give the final area at a given cross-section. From these areas the area distribution of the aircraft is obtained as shown in Fig. 9.

3.3.1 Cockpit Layout

Visibility rules and ergonomics rules are integrated in the CAD part to help the designer during cockpit design and integration. These design rules ensure basic certification requirements such as a comfortable seating position (independent of the pilot's body size and propositions), control devices placement and visibility. Two types of canopies can be designed:

- conventional external canopy
- fuselage embedded canopy

For better stealth benefits the fuselage embedded design may be chosen as the canopy blends with the fuselage resulting in a seamless integration. Both canopy types are designed around the pilots head taking into account the visibility and head clearance (see Fig. 10).

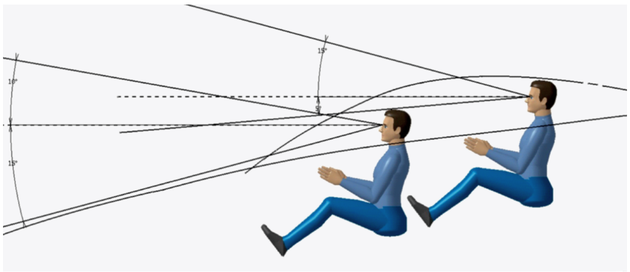


Fig. 10 : Cockpit layout of a tandem seat configuration

4 Model Management and Sensitivity Analysis

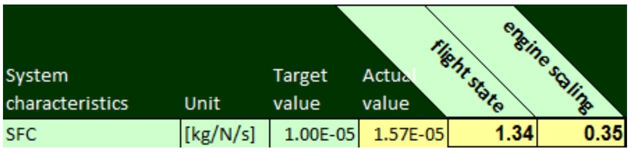
Model is on one hand related to the model input data such as the data handling, im-/export support ensuring data consistency and the supply of efficient user interfaces. On the other side - with focus on the design benchmark- it relates to the result data processing. The analysis and representation of the results from the applied analysis tools of different accuracy levels is a huge issue. One common method of weighting and assessment of result data towards its input data is a sensitivity analysis. This method simplifies in its easiest form the design into a strict linear dependency between the model design parameter (DP) and the resulting characteristics, called system characteristics (SC):

$$SC = A * DP \tag{1}$$

Applying this method on the aircraft data has the following benefits

- detection of critical (negative) or beneficial (positive) couplings and gain of overview and understanding of the design
- framework data structure analysis with a focus on the non-coupling terms. Every zero or close to zero term in the sensitivity matrix motivated by:
  I. Absence of connection between DPi and SCj
  II. Interaction of DPi and SCj is very small
  III. Counteracting positive and negative trends that eliminate each other (hard to detect!)

With respect to the framework (parametric) data structure development, case I and II implies that there is no parameter interaction or that the analysis methods do not take care of this input data. In the first case, the respective input data can be removed without accuracy loss, simplifying the model. The second case points out the analysis method is too grove or perhaps faulty implemented and should be revised or replaced. Case III can be avoided by analyzing the original, unreduced A matrix, where the DPis and SCjs represents the smallest possible units (down to Boolean or single value DPs).



System characteristics	Unit	Target value	Actual value	flight state	engine scaling
SFC	[kg/N/s]	1.00E-05	1.57E-05	1.34	0.35

Fig. 11 : Maximal reduced engine sensitivity matrix regarding thrust specific fuel consumption as the only design parameter with the design parameter "flight state" consisting of flight velocity and altitude and "engine scale factor" of reference trust, TET and BPR. (Remark: no reheater operation included)

One example of this analysis is the complex engine deck data: When calculating the aircraft mission performance by grove segments with the help of handbook methods, the propulsion system analysis will gain in the simplified sensitivity matrix shown in Fig.11. In this case, the usage of a rudimentary sizeable engine model, based on statistic values like e.g. [16] would have lead to the same result as the complex engine deck data.

5 Aircraft Simulation

For evaluating the performance of the aircraft in a realistic scenario a system simulation model was built that could be used in a mission simulation. The flight dynamics model is here based on a 6DoF rigid body model that is connected to an aerodynamic model. The aerodynamic model can have different number of wings or other lifting surfaces with an arbitrary number of control surfaces, and a body with its characteristics. It is here based on a static version of the model presented in [10], although the unsteady effects can of course also be included. The aircraft model is part of the Hopsan simulation package developed at Linköping University.

5.1 Mission Simulation

With the above described 6DoF aircraft model and additional Hopsan components, a whole aircraft mission simulation model is generated (Fig. 12). For this purpose, the primary flight control system (PFCS), including the hydraulic actuation system is modeled. The PFCS also includes a simple control system including a mission controller. A simple gas turbine model calculates the thrust and fuel consumption as a function of density, temperature and flight velocity. In this way, effects of failure modes can be simulated in order to analyze system reliability and derated system state performance [17]. The mission is a clean high altitude interceptor mission with a super-cruise to the target area and a subsonic return flight, see Fig. 13 and Fig. 14. Two main evaluation criteria are the mission time and the consumed fuel. The consumed fuel is then returned to the weight estimation loop.

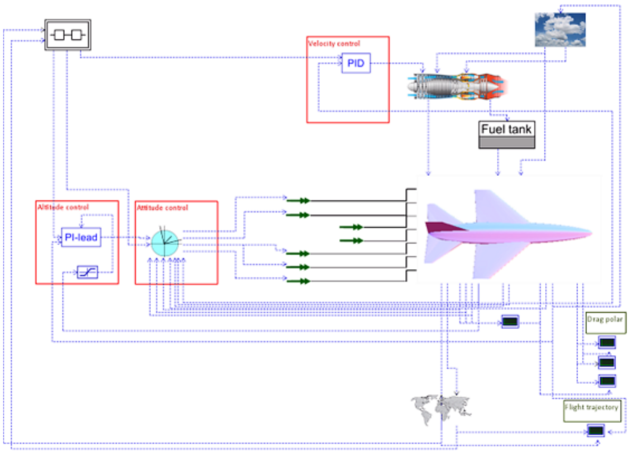


Fig. 12 : Hopsan system simulation model

6 Discussion

Holding all data together and consistent and include different tools into a framework proved to be a hard task if flexibility in the tools should not limited and a fixed defined working procedure should be avoided. In the presented framework, this topic was solved on the definition/input data by a flexible XML schema but with a rather limited design space. The later serves for an easier and more transparent integration of analysis tools or methods. More problematic are the analysis result data, where normally the quantitative rating of the result values regarding fidelity and sensitivity or robustness is not offered. First steps

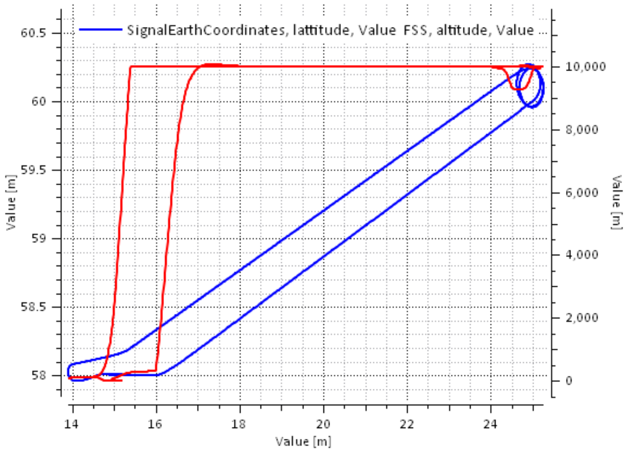


Fig. 13 : Simulated combat mission with high speed outgoing and subsonic cruise on the return (ground track in blue and altitude in red/secondary y-axis)

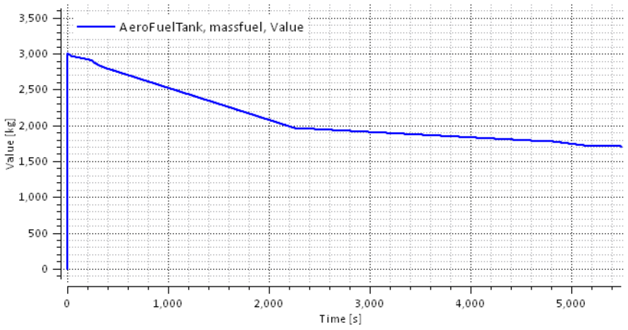


Fig. 14 : Consumed fuel for F-16 in baseline configuration

are taken here by the classification of different fidelity levels. However this is not sufficient because of the fidelity of different parameters may differ within a tool or method, so that the actions for data correction are still undefined.

In the VLM aerodynamic study, adding more lifting surfaces to the mesh after the grid convergence study will influence the results, and partially invalidate the convergence study itself. However, as long as the principal design based on the full geometry is checked against the wing-alone results, most detrimental effects are avoided. The method of determining the twist distribution will give a wing with good induced drag characteristics. It will, however, also load the tip of the wing more than appropriate for roll control. A highly loaded wing tip may stall, caused either by the roll rotation itself, or by the aileron deflection. Hence, the described method is only a step towards the final geometry.

As exceptional helpful within both, the aircraft designing process as well as for pure performance analysis, the total system simulation has proven to be an important part in such a framework.

7 Conclusion

A conceptual aircraft framework based on a central XML database has been explained and the application is shown on a reengineering example. Advantageous in this framework is the full 3D CAD environment on the one side and the powerful KBE related system simulation on the other side. Besides the low fidelity aerodynamic analysis (vortex lattice method), currently no higher level aerodynamic analysis capabilities are included in the framework but can be accessed via the XML interface capability.

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