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KNOWLEDGE-BASED FUTURE COMBAT AIRCRAFT OPTIMIZATION

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Abstract

Future combat aircraft inherently conceal all the components internally essentially for stealth reasons. The geometry is optimized for subsonic and supersonic flight area distribution and the components and payload to be fitted inside the aircraft. The basic requirements to accomplish are fuel consumption, mission profile, and military performance. Analytical methods comprise of a quick aerodynamic and structural optimization. The result obtained is then compared with multi-fidelity aero-structural analysis.

1 Introduction

The aircraft (FX5) presented by Munjulury et al.[1], is further studied and geometrical optimization is preformed. In order to minimize drag and signature, there is no vertical tail. Instead, thrust vectoring is contemplated to achieve high maneuverability and enhanced high AOA landing [2]. Furthermore, quicker rotation on take-off may be achieved leading to short take-off and landing (STOL) capability.

2 Objectives/Designing Studies

The fundamental objective of this investigation is to demonstrate the efficiency of the tools in designing and optimizing the configuration studied and the best geometric parameters found allowing to achieve:

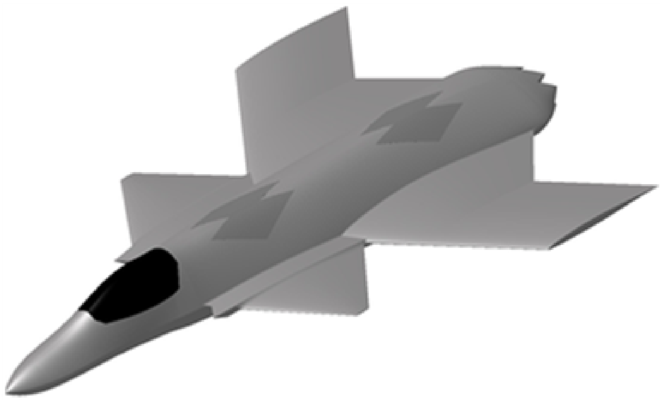

Fig. 1 : FX5 Baseline aircraft [1]

- High internal volume of the fuselage
  - Large volumetric capacity of fuel housed in the fuselage
  - Weapons systems
- Increase (armament) load capacity
- Reduce wetted area (for the configuration)
- minimum amount of the shock wave drag coefficient for cross-section area distribution

3 Methodology

Initially, a tailless supersonic combat aircraft concept is generated, including the fuselage, canard, and wing (see Fig. 1). RAPID (Robust Aircraft Parametric Interactive Design [3, 4]) program provides basic geometry modeling of the aircraft further used in a stochastic parametric

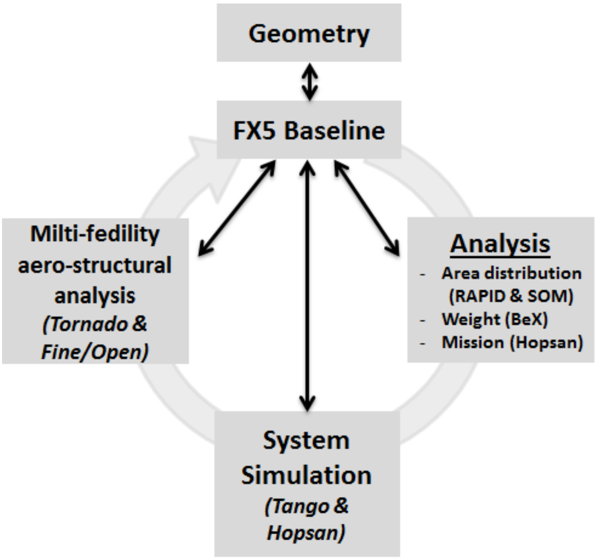

Fig. 2 : Framework for Optimization

method based on a database in SOM -Sonic Optimization Module.

The model is analyzed and evaluated by the aerodynamic and optimization module (SOM) and the new settings are determined to find the geometric parameters of the configuration satisfying the design requirements. Analytical and semi-empirical methods comprise of subsonic, transonic and supersonic aerodynamic drag computation.

SOM code, written in Visual Basic language, uses analytical and semi-empirical methods [5, 6, 7, 8] in solving the aerodynamic drag problem. Validation performed using open results from missile shapes and the F16 are presented by Cruvinel [9].

4 Optimization Framework

The optimization is performed by using different tools developed in the conceptual aircraft design framework [4] at the Linköping University within a national aviation research project (NFFP) started in 2009 [10]. Systems simulations and multi-fidelity aero-structural analysis are further utilized in the optimization.

4.1 Geometry

The FX5 aircraft geometry designed and developed in RAPID [3] and the preliminary work

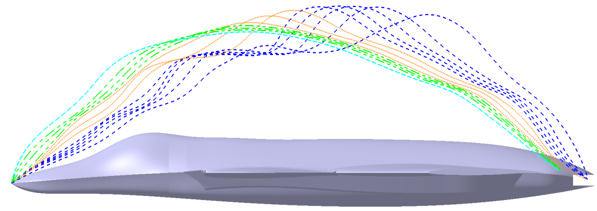

Fig. 3 : Initial effective area distribution for FX5 in RAPID, Mach numbers ranging from 1 to 1.4; 1.6 to 2; 2.1 to 2.3 and 2.5 [1]

of/on geometry presented in [4] is used in the optimization. The geometry consists of three main parts; fuselage, wing, and canard. Wing and canard geometries remain unchanged, only fuselage is optimized alongside canard and wing positioning.

The fuselage consists of ten cross-sections. Each of these is optimized for wave drag reduction of the whole aircraft. The cross-sections comprise of two Bezier cubic equations as represented in a matrix format in Eq. 1 [11]. As presented in [3] (Fig.6), point 1, point 4 and point 7 are dependent on the fuselage splines; Only point 2, point 3 point 5, point 6 values are required for the cross-section geometry modification, in both Bezier cubic equations (Eq. 1) points P2 and P3 are modified.

$$B(t) = U(t)A \tag{1}$$

where:

$$U(t) = \begin{bmatrix} t^3 & t^2 & t & 1 \end{bmatrix}$$

$$A = \begin{bmatrix} -1 & 3 & -3 & 1 \\ 3 & -6 & 3 & 0 \\ -3 & 3 & 0 & 0 \\ 1 & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} P_0 \\ P_1 \\ P_2 \\ P_3 \end{bmatrix}$$

$$\begin{bmatrix} P_0 \\ P_1 \\ P_2 \\ P_3 \end{bmatrix} = \begin{bmatrix} P_{0x} & P_{0y} \\ P_{1x} & P_{1y} \\ P_{2x} & P_{2y} \\ P_{3x} & P_{3y} \end{bmatrix}$$

4.2 Sonic Optimization Module (SOM)

For initial wave drag estimation, Raymer method [12] is adopted. Unlike other empirical methods, the Raymer approach takes the geometry and dimensions of the wing and fuselage into account.

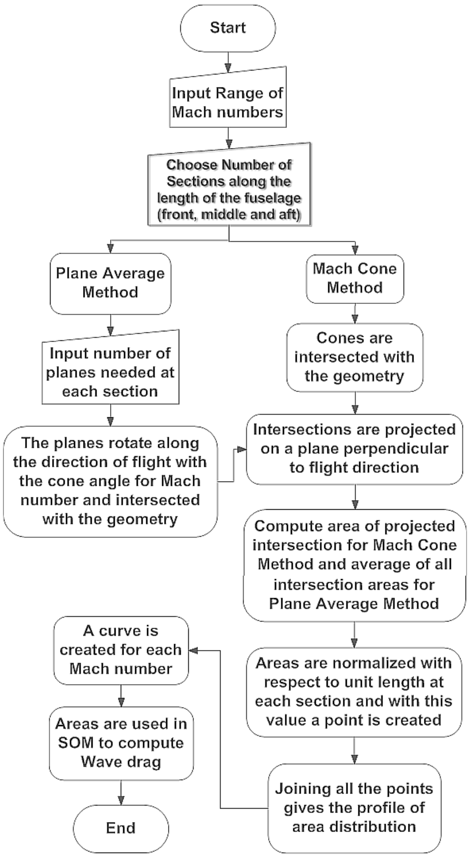

Fig. 4 : Area distribution flow process in RAPID

However, the reliability of this approach is unknown, so the supersonic drag calculated by this method should be handled with care; it might be sufficient for initial studies and conceptual aircraft design.

E_{WD} is defined by the correlation between the aircraft and the Sears-Haack body wave drag, normalized to the wing reference area (Eq. 2):

$$C_{WD} = \frac{E_{WD}}{S_{ref}} \left[1 - 0.396(M-1.2)^2 \left(1 - \frac{\Pi \Lambda_{LE-deg}^{0.77}}{100} \right) \right] \frac{D}{q}_{Sears-Haack} \tag{2}$$

Λ_{LE-deg} = *Leading edge sweep angle*
E_{WD} = *Empirical wave drag efficiency*
M = *Mach number*

The methodology presented in [9] to calculate the wave drag coefficient of Sears-Haack body considers drag for Sears-Haack body using (Eq. 3).

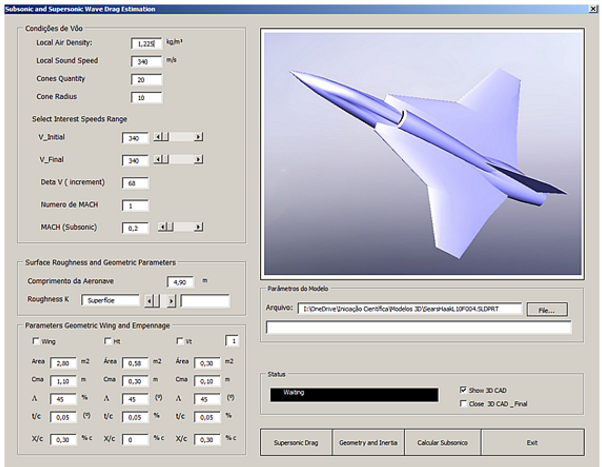

Fig. 5 : Subsonic and Supersonic Estimation program - SOM

$$\frac{D}{q}_{Sears-Haack} = \frac{9\pi}{2} \left(\frac{A_{max}}{l} \right)^2 \tag{3}$$

With the (known) approximate total volume of the aircraft (Eq. 4), the body can be modeled as a cylinder with rounded ends (Eq. 5).

$$V_{body} = \int_0^1 A_{cross-section}(y) dy \tag{4}$$

$$V_{body} = \pi (l - 2r) r^2 + \frac{4\pi r^3}{3} \tag{5}$$

The aircraft maximum equivalent cross section area A_max can be extracted by Eq. 6.

$$A(x) = \frac{V_{tot}}{l} \left[1 - \left(\frac{x}{l/2} \right)^2 \right]^{2/3} \tag{6}$$

E_{WD} in Eq. 2 is the empirical wave drag (efficiency) factor. It represents the ratio between the real wave drag and the wave drag of a Sears-Haack body.

Applying the Linearized Supersonic flow theory to speeds close to Mach 1.0, one can notice that the wave drag of a system of body and wings only depends on the longitudinal area distribution of the system as a whole. If the speed is equal to Mach 1.0, the expression for the wave drag becomes Theodore von Kármán's formula for the wave drag of slender bodies of revolution:

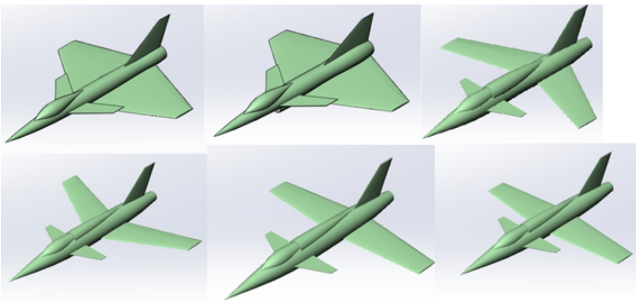

Fig. 6 : An example of geometry optimization using SOM

$$D_{M\to 1} = -\frac{\rho V^2}{4\pi}\int_{-x_0}^{+x_0}\int_{-x_0}^{+x_0} S''(x)S''(x1)\,log|x - x1|\,dxdx1 \quad (7)$$

Where $S(x)$ represents the cross-sectional area intercepted by a plane perpendicular to the stream at a distance x from the tip of the body.

The approximations shown in Eq. 4, Eq. 5 and Eq. 6 have not been used in the Sonic Optimization Module (SOM), developed by Cruvinel [9] & Abdalla; instead, the geometry analysis is directly performed on behalf of the parametric CAD/geometry model.

The tool is based on a semi-analytical method of [8] (Eq. 7). SOM can quickly generate various aircraft configurations, and calculate the areas of the cross sections for any Mach number. A generic algorithm (GA) is included for the geometry manipulations. Another advantage is that the E_{WD} value can also be directly estimated by comparison of the normal Sears-Haack body volume with the aircraft volume.

4.3 Aircraft Mission Simulation

With the help of the analytic data, a six degree of freedom (6-DOF) simulation model is build-up. The model is based on work from [13] and nowadays part of the standard distribution of Hopsan [14]. The central part of this simulation model is a 6-DOF dynamic model of an airplane, embracing ca. 100 parameter, most of them normalized such that scaling/design adaptions can be performed by a few parameters only, holding the remaining in a valid condition by appropriate selection of the normalization factors.

4.3.1 6-DOF Aircraft Model

Table 1: Overview of the 6DOF simulation model parameter categories.

Parameter Category	Nr. of parameters
geometry	26
controls geo	13
controls aero	9
aero	25
environmental	8
weight	7
propulsion	6
model	6

Drawback of this minimalistic but complete aircraft model description is the absence of geometry information needed to render the setup geometry for a visual user interface (e.g. for visual input data check). Basic geometry properties have to be (re-)calculated from aerodynamic properties such e.g. the taper ratio from the Oswald factor (with known aspect ratio).

4.4 Analysis

Concept performance is analyzed mainly on the following aspects:

- Geometry (as the input)
- Weight, Balancing, and Trim
- Aerodynamic
- Propulsion

Weight is mainly a result of the chosen/defined geometry and propulsion (engine selection). By analysis in BeX, weight estimation based on SAWE methods (see [15]) is conducted. Aerodynamic analysis is split between the tools: Hurricane-CS for control surface sizing, BeX serving for the trim and trim drag, Tornado for calculation of the aerodynamic coefficients, and finally SOM for the wave drag estimation.

4.4.1 BeX

BeX is an aircraft sizing, weight estimation, drag prediction, balancing, and cabin layout program built in Excel. The user begins with inputting the desired geometry and requirements. Engine type and number of engines are determined by the necessary thrust. The weight of the aircraft calculated according to weight penalty method also provides drag estimations.

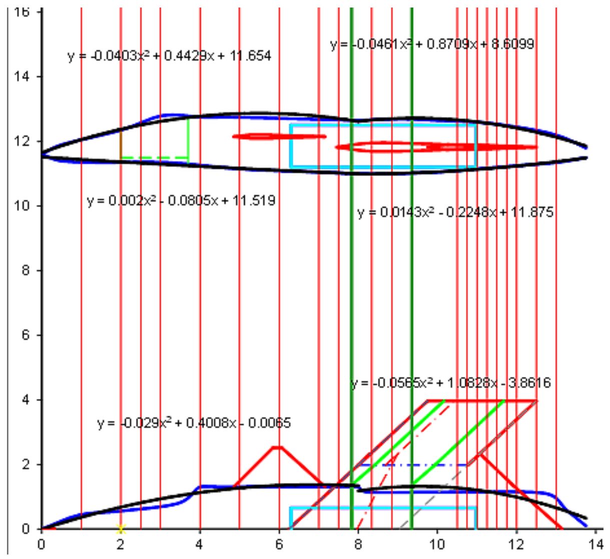

Fig. 7 : BeX Sizing and Structural weight estimation using weight penalty method

4.4.2 Tornado and HURRICANE-CS

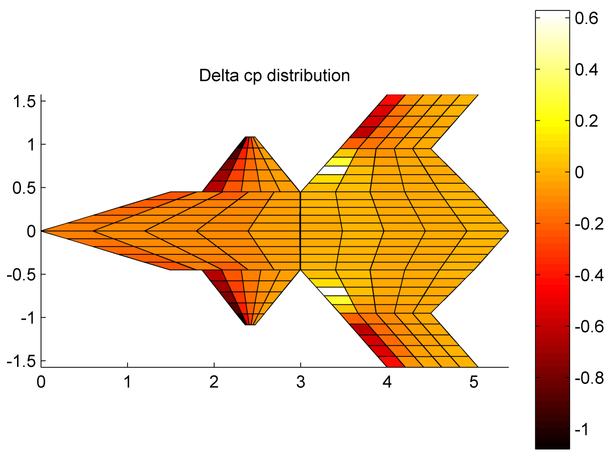

Fig. 8 : Pressure distribution of the Tornado model at 4.5 degrees angle of attack

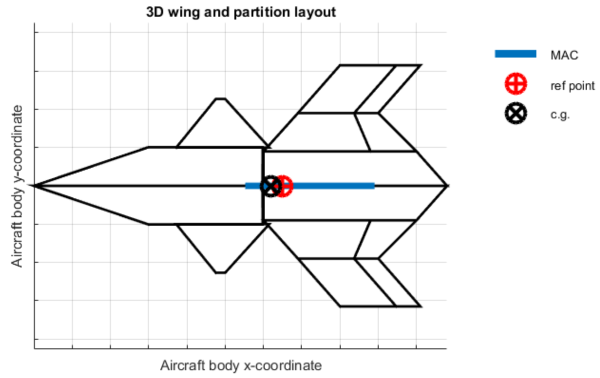

Fig. 9 : FX5 control surfaces in HURRICANE-CS

Tornado is a vortex lattice method (VLM), implemented in Matlab® [16]. It is used to determine the aerodynamic coefficients including control surface coefficients. Model geometry is flattened from the CAD model into Tornado notation therefore complex body geometries are not supported. As an approximation, the body is modeled by lifting surface partitions like the wing and the canard, too. Due to this simplification, friction drag prediction might be inaccurate.

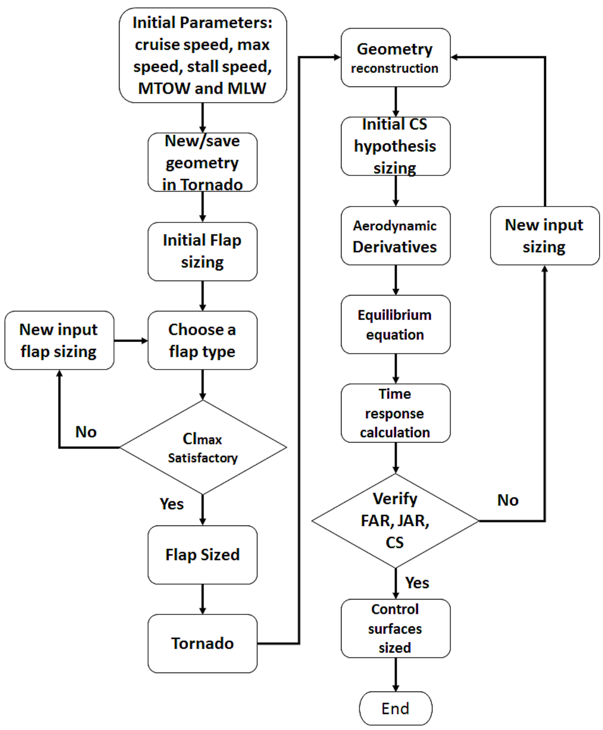

Fig. 10 : HURRICANE-CS flow chart

HURRICANE-CS, developed in Matlab® as a complimentary to Tornado, allows an automated sizing of the primary and secondary control surfaces out of a number of known parameters of an airplane. Initial hypothesis [12, 15, 17, 18] size the control surfaces required for the aircraft. After obtaining the initial parameters from BeX and geometry from Tornado, HURRICANE-CS performs the following:

- Lift criteria size flaps for take-off and landing
- Automatic measures of ailerons, rudder, and elevator based on load cases
- Solves equilibrium and dynamic equations to obtain time response
- Checks the requirements and iterates the process until the conditions fulfillment.

An overview of the control surface sizing process is shown in Fig. 10.

4.5 Optimization

The optimization processes connecting several disciplines such as geometric model, aerodynamic model, structural model, wave drag model and the simulation model is shown in Fig. 11. The first estimate of control surfaces size is performed using BeX, Tornado, and HURRICANE-CS. SOM and RAPID work together in a local optimization loop to optimization each cross-section of the geometry. For this purpose the matrix form of Bezier curve (Eq. 1) implemented in RAPID are used.

$$Min : W(x), C_D(x) \tag{8}$$

Subjected to:

$g(x) : V_f(Required) \leq V_f$
$h(x) : \sigma \leq \sigma_{Critical}$
$k(x) : S_{ref} * C_{L(Critical)} \leq S_{ref} * C_L$
$m(x) : M_f x_{low} \leq x_i \leq x_{up}$

M_f = *Mission fulfillment*
$MTOW$ = *Maximum Take off weight*
W = *Weight of the aircraft*
V_f = *Fuel Volume*

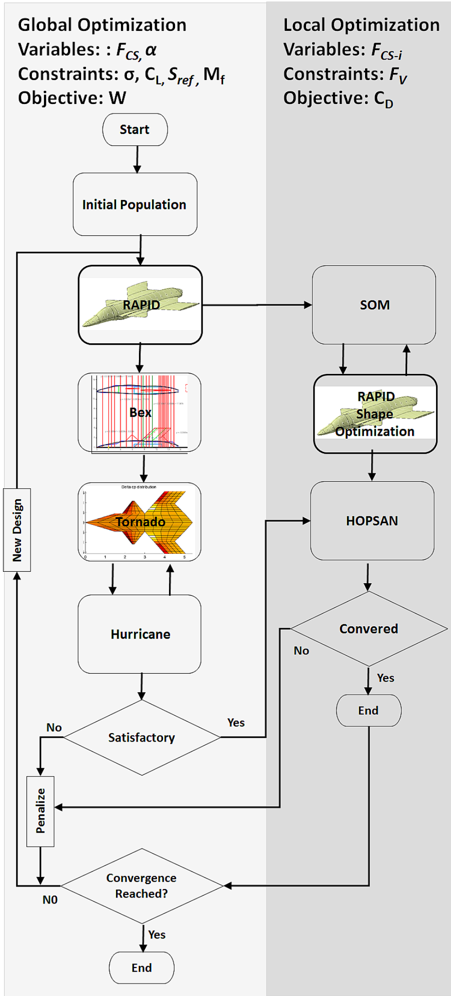

Fig. 11 : Integrated Multidisciplinary Optimization Framework

S_{ref} = *Reference Area*
σ = *Bending stress*
F_{CS-i} = *Fuselage Cross-section*
F_V = *Fuselage Volume*
C_L, C_D = *Coefficient of Lift and Drag*

5 Results and Discussions

Area distribution is performed in different ways, the capture area is deducted from all the cross-section area for the calculations. The initial geometry (Fig. 3) shows area distribution without inlet area reduction, Fig. 12 illustrates with deduced capture area from the maximum cross-section area. The geometry is first minimized manually at the engine location to reduce the drag and start with a design closer to the solution. The optimization is performed using NSGA-II with 40 individuals and 50 generations. The figure shows the area distribution for initial, intermediate and one of the optimized geometries for the design Mach number of 1.3; the wave drag for initial and optimized geometry are 0.272 and 0.2406.

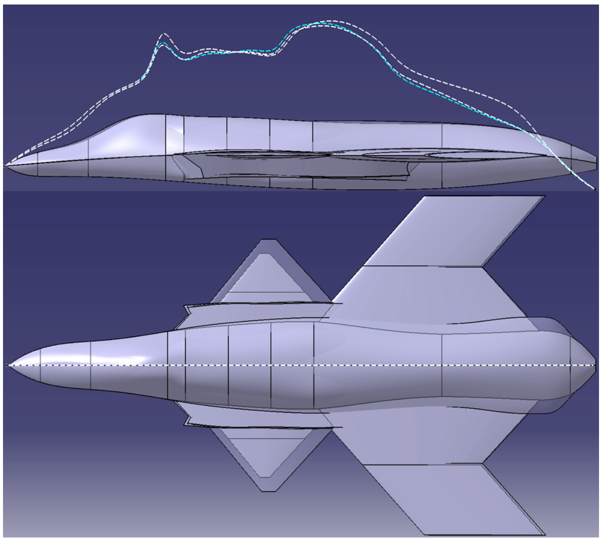

Fig. 12 : Area distribution of initial, intermediate and optimized geometry(top); Optimized FX5 (bottom - initial geometry in light gray and optimized geometry in dark gray)

A smooth area distribution reduces the supersonic drag of the aircraft. The region between the two peaks in the Fig. 12 are smoothed for minimizing the wave drag. The optimization has reduced the wave drag of the aircraft considerably. The first peak occurs at the start of the inlet and the second peak at the beginning of wing, these geometries add up to total volume and is not avoidable. Therefore, the optimization smooths the region between the peaks by adding extra volume to hold additional entities.

6 Conclusion

This paper presents an optimization, combining an aircraft design framework with a supersonic wave drag analysis and optimization module, SOM. In previous tests, the SOM-RAPID-Tango programs have proven to be effective in communicating with the module used for the calculation of aerodynamic optimization and CAD modeling. The aerodynamic module has been successfully used to assess the aerodynamic drag of subsonic and supersonic aircraft and missiles. The optimization module effectively demonstrates generating military aircraft whose configuration comply with spin recovery maneuver requirements. Design evaluation by means of simulation models proved to be a reliable method, especially for unproven concepts with the absence or misalignment of statistical data.

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References

[1] Munjulury R C, Staack I, Abdalla A, Melin T, Jouannet C and Krus P. Knowledge-based design for future combat aircraft concepts. *Proc. 29th Congress of the International Council of the Aeronautical Science, St. Petersburg, Russia*. 2014.

[2] Jouannet C and Krus P. Unsteady aerodynamic modelling: a simple state-space approach. *AIAA Aerospace sciences meeting and exhibit*. Reno, USA, 2005.

[3] Munjulury R C, Staack I, Berry P and Krus P. A knowledge-based integrated aircraft conceptual design framework. *CEAS Aeronautical Journal*, vol. 7, no. 1, pp. 95–105, 2016.

[4] Staack I and et al. Parametric aircraft conceptual design space. *28th Congress of the International Council of the Aeronautical Science*. Brisbane, Australia, 2012.

[5] Whitcomb R. A study of the zero-lift drag-rise characteristics of wing-body combinations near

the speed of sound. *National Advisory Committee for Aeronautics, NACATR-1273*, 1956.

[6] Ashley H and Landahl M. *Aerodynamics of wings and bodies*. 1st ed. Dover Publications Inc., New York, 1985.

[7] Seebass R. Supersonic aerodynamics: Lift and drag. *Aerospace Engineering Sciences*, pp. 1–6, 1998.

[8] Jones R T. Theory of wing-body drag at supersonic speeds. *National Advisory Committee for Aeronautics, NACATR-1284*, 1956.

[9] Cruvinel J P M C. *Implementation of a Method for Estimating Shock Wave Drag*. EESC / USP / Aeronautical Engineering Course -TCC, 2015.

[10] VINNOVA. Swedish national aviation engineering research programme, "[Online; Accessed 27-June-2016]". http://www.vinnova.se/en/Our-acitivities/Cross-borde-co-operation/Cooperation-Programmes/National-Aviation-Engineering-Research-Programme/.

[11] Chang K H. *Design Theory and Methods Using CAD/CAE: The Computer Aided Engineering Design Series*. Academic Press, 2014.

[12] Raymer D P. Aircraft design: A conceptual approach, american institute of aeronautics and astronautics. *Inc, Reston, VA*, 1999.

[13] Krus P. Whole mission simulation for aircraft system design. *AST 2009 Workshop on Aviation System Technology*. 2009.

[14] HOPSAN, "[Online; Accessed 27-June-2016]". http://www.iei.liu.se/flumes/system-simulation/hopsan?l=en.

[15] Berry P and Jouannet C. Recycling old weight assessment methods and giving them new life in aircraft conceptual design. *28th Congress of the International Council of the Aeronautical Science*. Brisbane, Australia, 2012.

[16] Melin T. A vortex lattice matlab implementation for linear aerodynamic wing applications. *Master's Thesis, Department of Aeronautics, Royal Institute of Technology (KTH), Stockholm, Sweden*, 2000.

[17] Sadraey M H. *Aircraft Design: A Systems Engineering Approach*. John Wiley & Sons, Chichester, West Sussex, 2012.

[18] Roskam J. *Airplane design*, vol. 2. Roskam Aviation and Engineering Corporation, 1985.

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