Analysis of Radar Cross Section and Wave Drag Reduction of Fighter Aircraft

Uandha Fernandes Barbosa*, João Paulo Monteiro Cruvinelda Costa*, Raghu Chaitanya Munjulury**and Alvaro Martins Abdalla*

*DepartmentOfAerospace Engineering, Engineering Schoolof São Carlos, University of São Paulo, 400 Trabalhador São-Carlense Avenue, São Carlos, São Paulo 13.566-590, Brazil

*(E-mail: uandha.barbosa@usp.br; joao.monteiro.costa@usp.br; pfalvaro@sc.usp.br)

**Department Of Management and Engineering, Division of Fluid and Mechatronic Systems, Linköping University, s-581 83 Linköping, Sweden

**(E-mail: raghu.chaitanya@liu.se)

Abstract

Stealth or low observability, high speed and maneuverability are very important characteristics for modern military aircraft. Planform shaping is fundamental to achieve stealthy aircraft. As well as Radar Cross Section (RCS), the supersonic aerodynamics characteristics are crucial to achieve the optimum.In order to follow the current trend of the military field in stealth designing and application, this study on supersonic aircraft geometries is investigated in both aspects. Using Soliworks® software, 3D CAD models were developed and designed. Using the tool SOM, it was possible to choose the aircraft model with lowest wave drag coefficient ($CD_{wavedrag}$*). The RCS part of this model was simulated using POFACETS software. This program was developed by Naval Postgraduate School (NPS) under the MATLAB® platform. It is based on physical optics (PO) method to predict the RCS targets (3D CAD models) using triangular facets. The radar signature analysis are done to : a) investigate the dependency of stealth characteristics with high frequency b) chose the one with lower RCS signature. Finally, the results of stealth-aerodynamic of 3D CAD models were contrasted and summarized.*

Keywords: Aerodynamics, Military, Radar Cross Section, Stealth, Supersonic, Wave Drag.

Introduction

The concept of survivability came to light in World War I; when air attacks became a valuable asset to improve the odds. Especially in World War II, radar and surface to air missiles posed an increasing threat to aircraft (Wilson, 2004). Overall low observable aircraft had better strike capabilities and a higher chance of completing the mission. Focusing on the question *"how to became more invisible to the radar?"* the efforts to design external parts of an aircraft with minimum Radar Cross Section (RCS) are primordial. Since that time, many researches in this field have been carried out on many aspects such as fuselage, wings, inlets and materials (Wood and Bauer, 2001).

The information about shapes for low radar detection and parameters that are compatible with the structural and aerodynamic requirements is necessary during the preliminary design phase of an aircraft. The RCS analysis is a powerful mechanism that provides support for an aircraft's conceptual design and stealth optimization. Aerodynamic properties are indispensable for the overall performance of an aircraft. These should always be taken into account during design phase.

This paper conducts studies on theoretical models designed for the purpose of demonstrating the importance of the shape in the RCS of an aircraft. Furthermore it is possible to identify the most vulnerable areas. However an ideal design consists of an aircraft capability to survive in mission. And for this goal it is necessary to have equilibrium between RSC and aerodynamics. Consequently it is expected that the results will provide guidance and technical support during the conceptual design for aerodynamics-stealth aircraft.
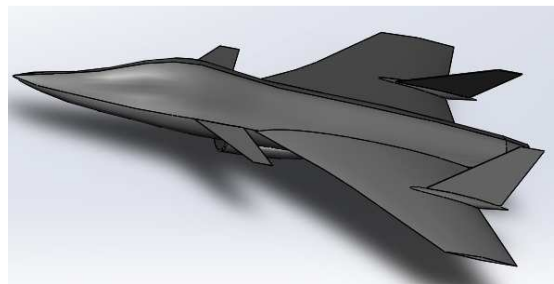
CONCEPTUAL DESIGN

Models designed can be seen in Fig.1, Fig. 2, and Fig. 3. They were developed to be capable of flying at supersonic speed. These models could be operational aircrafts since they have single seat and their aerodynamics parameters were simulated by a computational tool called SOM Program (Cruvinel da Costa, J.P.M. & Abdalla, A. M., 2015). The common layouts between all three prototypes are the fuselage, the span and the canard. Some these characteristics are presented in Table 1. Vertical stabilizer and intake location are the variables considered during the analysis.

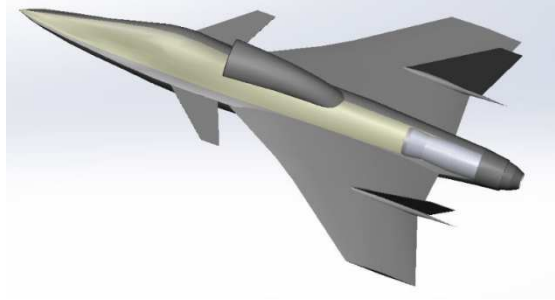| Parameter	Size
Length	15,80 [m]
Span	10,04 [m]
Engine Numbers	1
Root Chord	6,76 [m]
Wing Area	35,12 [m²]
Canard Area	3,35 [m²]
Total Vertical Stabilizers (VT) Area	5,60 [m²]
Leading Edge Sweep Angle	58,04°

Table 1: Basic parameters of the conceptual models.

The 3D CAD prototypes are designed with SolidWorks[1]® software including basic parameters. The models schemes are shown below. After the conceptual design, the RCS characteristics are numerically simulated so as to analyze the stealth performance.
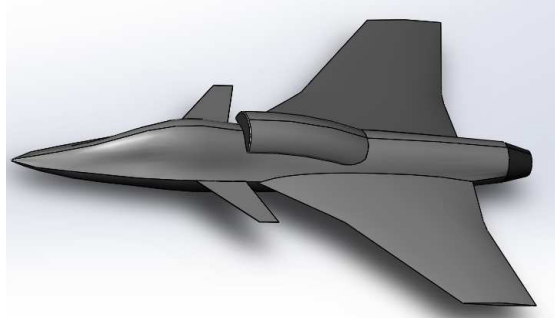

Figure 1: Model Ventral Intake (M_I).

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[1]   SolidWorks®is a 3D CAD (computer-aided design) software developed by SolidWorks Corporation.

Figure 2: Model Dorsal Intake with V Tail (M_VT).

Figure 3: Model Dorsal Intake with Tail-Less (M_TL).

THEORETICAL BASIS

The theoretical basis of stealth and aerodynamics of combat aircraft includes the study of the wave drag phenomena, understanding of the RCS calculation and the integration of the both information, stealth-aerodynamic which allows investigating the connection between stealth requirements and aerodynamic properties.

Wave Drag and Sears-Haack Body

The wave drag estimation was initially based on Raymer method (Costa & Abdalla, 2015). Unlike other empirical methods, Raymer approach takes into account the geometry and dimensions of the wing and fuselage. The reliability of this method is sufficient for the initial studies and conceptual aircraft design, since it is based on the comparison between the geometries.

The wave drag coefficient is calculated using a correlation with the Sears-Haack body as follows:

$$c_{DW} = \frac{E_{WD}}{S_{ref}} [1 - 0,396(M-1,2)^2 (1 - \frac{(\pi \Lambda_{LE\text{-}deg}^{0,77})}{100}](\frac{D}{q})_{sears\text{-}Haack} \tag{1}$$

where: Λ_{-deg} is the sweep angle in the leading edge; E_{WD} is the empirical wave drag efficiency and M is the Mach number.

The methodology (Costa & Abdalla, 2015) to calculate the wave drag coefficient of Sears-Haack body considers drag for Sears-Haack body as follows:

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

The whole volume of the aircraft and the volume of the body (V_{body}) are estimated by a cylinder with rounded ends using equations 3 and 4.

$$V_{body} = \int_0^1 A_{crosssection}(y)dy \tag{3}$$

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

The aircraft maximum equivalent cross section area A_{max} can be extracted from Eq. 5.

$$A(x) = \frac{V_{tot}}{l}\left[1 - \left(\frac{x}{\frac{l}{2}}\right)^2\right]^{2/3} \tag{5}$$

E_{WD}: in Eq. 1 is the empirical wave drag factor and efficiency represents the ratio between the real wave drag and wave drag value Sears-Haack body.

SOM Program

The SOM program (Fig.4) was used to compute Subsonic and Supersonic Drag with semi-analytical method instead of Raymer method. This approach is based on R. T. Jones paper "Theory of wing-body drag at supersonic speeds" and Whitcomb's "Area Rule".
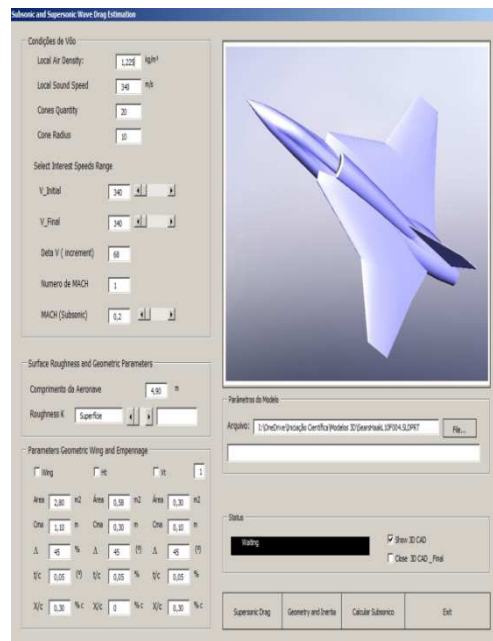

Figure 4: Subsonic and Supersonic Estimation program - SOM (Costa & Abdalla, 2015).

That was possible because the software can quickly generate various aircraft configurations and calculate the areas of the cross sections for any Mach number. This provides more accuracy to the method. Furthermore the software also estimates the E_{WD} value.

For speeds close to Mach 1 and based on Linearized Supersonic flow theory the wave drag coefficient depends only on the longitudinal area distribution. Theodore von Kármán's formula is a particular case when Mach 1 speed is considered on the wave drag equation. For the wave drag of slender bodies of revolution:

$$D_{M \to 1} = \frac{\rho V^2}{4\pi} \int_{-x_0}^{x_0} \int_{-x_0}^{x_0} S''(x)S''(x_1)log|x - x_1|dxdx_1 \tag{6}$$

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.

Radar Cross Section

The Radar Cross Section of a target is a measure of its visibility to radar. The RCS can be defined as the power scattered from a target to a certain direction, when the target is illuminated by electromagnetic radiation (Alves, Port & Mirabel, 2007). Concerning monostatic radars, RCS is a measure of the backscatter or radar return of a target. Therefore a larger value of this measure means high detectability by radar. Summarizing into a single term, monostatic RCS, in terms of electric field, σ is

$$\sigma = \lim_{r \to \infty} 4\pi r^2 \frac{|E_s|^2}{|E_I|^2} \tag{7}$$

where: r is the distance between the target and the radar, E_s, E_I are the scattered and incident electric fields, respectively.

The Eq. 7 is valid when the target is illuminated by a plane wave. This is a necessary approximation to satisfy the boundary far-field condition. RCS value must be in square meters. Due to the large range of values, it's usually in a decibel scale. The conversion of scales can be presented as follow:

$$dBSm = 10\log\left(\frac{\sigma}{1m^2}\right) \tag{8}$$

Typical RCS values for various targets can be found in Table 2.

Target	RCS [m²]	RCS [dBSm]
Insect	1.10^{-5}	-50
Bird	1.10^{-2}	-20
Adult	1	0
Automobile	100	20
Jumbo Jet	100	20
Small Fighter Aircraft	2	3
Large Fighter Aircraft	6	7,78
Advanced Tactical Fighter	1.10^{-6}	-60

Table 2: Typical RCS values of various targets at X-Band (Applied Technology Institute).

Methods to Predict Radar Cross Section

There's a variety of methods to calculate RCS. These methods are based on moments, finite difference, microwave optics and optical physics. Each of them requires a different computational run time to perform the analysis.
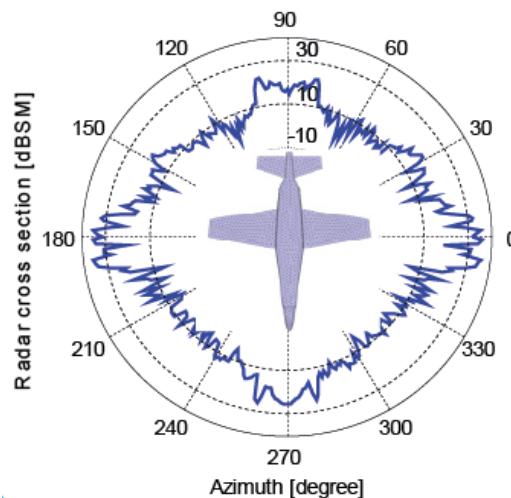
Several types of modeling and visualization of radar exist. Geometric modeling of solids, modeling by borders, modeling by Curved Patches, and Modeling by Facets are some of the techniques for predicting radar cross section. These require a realistic model of the target to impose boundary conditions of the electromagnetic problem on its surface (Rius Casals, 1991). The most common method used nowadays is modeling by borders through flat facets, in which the modeled surface is more realistic and results more accurate (Rius Casals, 1991).

Physical optical model is another of the techniques most commonly used nowadays to predict cross section of complex radar targets. It is obtained by consistently adding the contributions from each of the illuminated areas (Garrido, 2000). Because the physical optics method approximates the currents on the surface of the object to currents that would be on an infinite tangent plane, it provides good results with radar targets of large dimensions. Still it consumes the least amount of computational resources and is less complex (Garrido, 2000).

Within the arguments above, the computational resource used in this is study was the POFACETS 4.2(ref. 5). The software was developed in MATLAB[2]® platform. It allows approximation of RCS by using the physical optics method via facets and models imported from existing CAD.

Stealth Signature

Even a low observable aircraft will have its good sides and its bad sides. The radar cross section of an aircraft will be a consequence of the enemy's radar's position. A typical stealth aircraft signature might be as shown in Fig. 5 (EMCOS-Consulting and Software).

Figure 5: Typical Radar Cross Section Signature (EMCOS-Consulting and Software).

For any these signature shapes, the low observability of aircraft also depends on the wavelength. The RCS values vary with wavelength because it is one of the factors that determine the area of the radar cross section. This work only calculates RCS considering high frequencies. The reason for this is that radar operating in L-band (lower frequencies) produces wavelengths with comparable size to the aircraft itself and should exhibit scattering in the resonance region rather than the optical region, so that most of the existing stealth aircraft will turn from invisible, to visible.
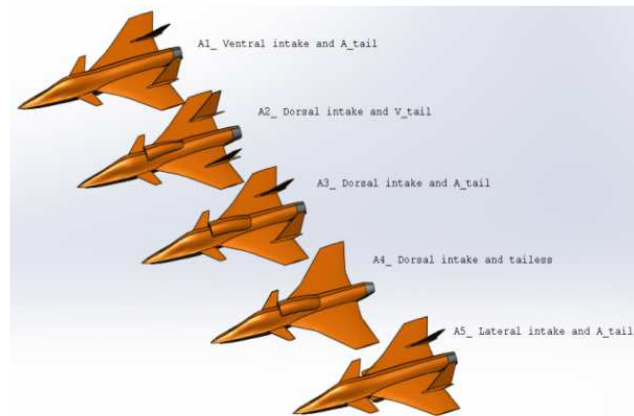
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[2]   MATLAB ® (matrix laboratory) is multi- numerical computing environment develop by MathWorks.

The goal for any low observable aircraft designer is to reduce spikes and to control their directions. It's possible to concentrate most of the reflections on a few directions aiming to reduce the RCS on all other directions.
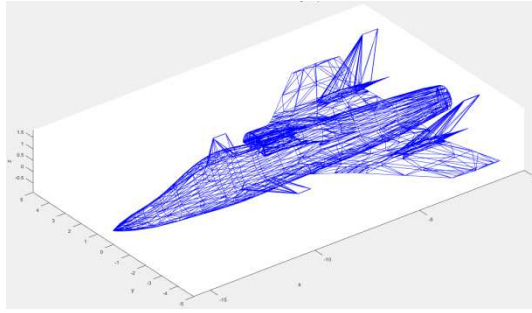
METHODOLOGY

The steps for analysis of the stealth-aerodynamic for this work follow the order in two mains parts: aerodynamic and radar signature. Firstly, in VBA script, the designs of the fuselage, intake and canard were parameterized. On the other hand, wings and vertical stabilizer were standardized. Fifteen different sketches were made for these single-engine aircraft: a) dorsal intake and A stabilizer; b) dorsal intake and V stabilizer; c) dorsal intake; d) thinner intake and A stabilizer; e) thinner intake and V stabilizer; g) thinner intake; h) ventral intake and A stabilizer; i) ventral intake and V stabilizer; j) ventral intake; k) thinner ventral intake and A stabilizer; l) thinner ventral intake and A stabilizer; m) thinner ventral intake and V stabilizer; n) thinner ventral intake; o) lateral intake and A stabilizer; p) lateral intake and V stabilizer; q) lateral intake. Some representatives' sketches of the group are show in Fig. 6. Three of the group were picked out once their models presented lower values for $CD_{wavedrag}$(wave drag coefficient). For estimate this coefficient tit was used SOM (Costa & Abdalla,). SOM´s method for approximation of subsonic and supersonic wave drag is considered partial analytical. Also it is based in R. T. Jones description (ref. 13). In addition Open VSP Version 3.9.0 and VSPAERO Version 3.0 software could help checking the results.

For the RCS studies, the computer-aided design (CAD) models shown above were developed to be the studied. With the Solidworks® software, each surface´s model is simplified into triangular elements and imported into POFACETS for the simulations. Figs. 7, 8 and 9 show the CAD models of the aircraft used in the simulations. Its surface was composed by 3168 (scheme M_VTL), 3012 (scheme V_I), 2556 (scheme M_TL) triangular elements respectively.
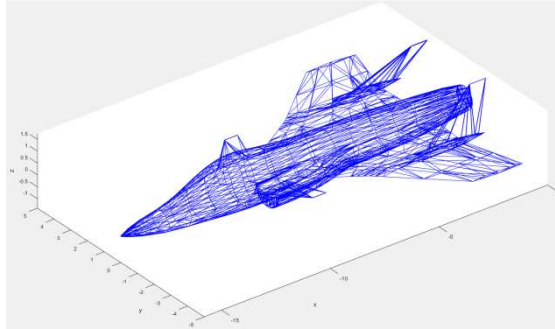

Figure 6: Figure 6: Representatives 3-D aircraft´s models for aerodynamics analyses. From the top to bottom : a) ventral intake and A tail; b) dorsal intake and V tail; c) dorsal intake and A tail; d) dorsal intake e) lateral intake and A tail.
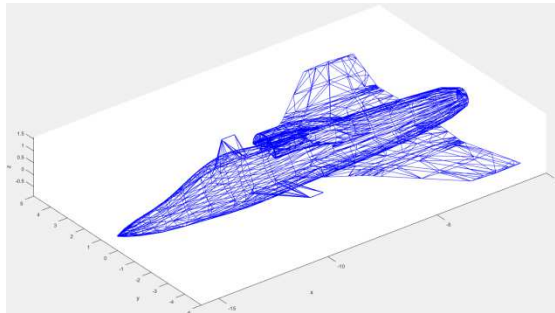
Some assumptions will be made as well as the radar is only monostatic case and the target involved with the high frequency (X-Band) range. That is because the stealth aircraft is detected in low frequency (L-Band) once radar produces wavelengths with comparable size to the aircraft itself. Therefore these terms allow applied physical optics method and shaping method. Following the steps is RCS calculation and the analysis basis in both results.

Figure 7: Triangular facet surface scheme M_VT.

Figure 8: Triangular facet surface scheme M_I.

Figure9: Triangular facet surface scheme M_TL.

RESULTS AND DISCUSSION

The supersonic wave drag data results are shown on Table 3. The aircrafts models with lowest wave drag in the simulations were made by SOM tool. Right below, on Table 4, there are the supersonic wave drag coefficients simulated on OPEN VSP.

Mach Number [-]	M_VT [-]	M_I [-]	M_TL [-]
1	0,065	0,088	0,066
1,2	0,059	0,064	0,062
1,4	0,052	0,053	0,046
1,6	0,044	0,046	0,042
1,8	0,035	0,037	0,038

Table 3: Simulated wave drag coefficients with SOM program.

Mach Number [-]	M_VT [-]	M_I [-]	M_TL [-]
1	0,065	0,082	0,065
1,2	0,053	0,054	0,055
1,4	0,051	0,047	0,048
1,6	0,041	0,045	0,044
1,8	0,037	0,039	0,044

Table 4: Simulated wave drag coefficients with OPEN VSP.

The dorsal intake with V tail model (M_VT) was the model with minimum wave drag coefficients based on Table 3 and Table 4 results (considering the mean wave drag coefficient for the 5 Mach numbers).
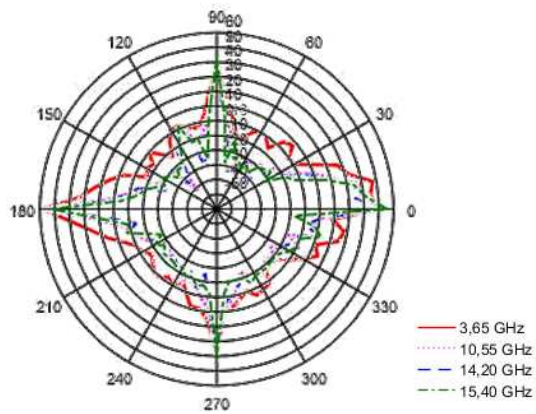
For the other part of the study, the physical optical method and TM polarization were applied for the RCS numerical simulation. Based on assumptions described above, the frequency bands that were chosen in this paper follow the guidelines of Federal Radar Spectrum Requirements (ref.17) (Table 5).

On the polar coordinates of the aircraft's RCS characteristic, the azimuth angle 270° corresponds to the head direction of the aircraft and the azimuth angle 90° corresponds to the tail direction of the aircraft. The azimuth angle 0° is the right side of the aircraft. The assumption for nearby RCS analyses are: a) values between 30° to 330° and 210° to 150° (aircraft´s sides); b) between 60 ° and 120° (aircraft´s back); c) between 240 ° and 300° (aircraft´s front).
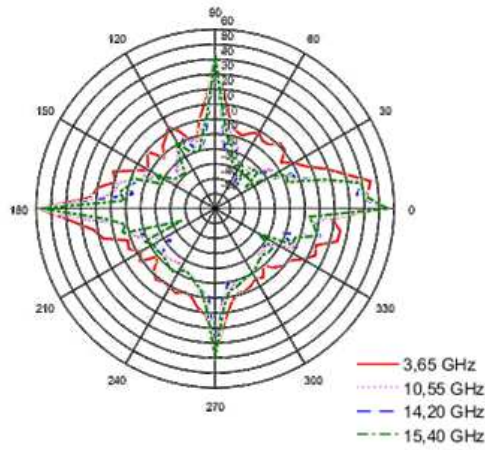
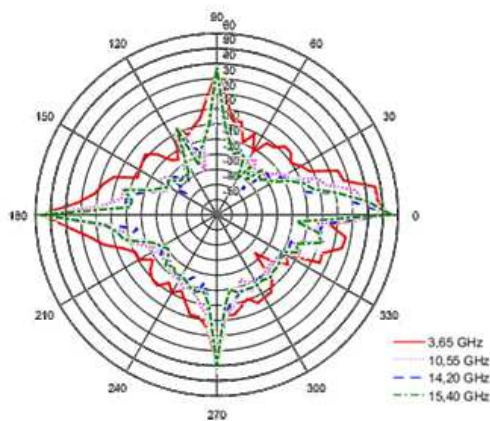| Band	Frequency [GHz]
S	3,65
X	10,55
Ku	14,20
K	15,40

Table 5: Radars Bands for RCS simulation.

The polar graphics (plotted into POFACETS) are shown on Figures 10, 11 and12, respectively. The pattern observed in these signatures follow the same aspect: the green line is closer to the center of the graphic. Therefore the minimum signature is represented by this frequency. For all three aircraft's models, (M_I, M_TL and M_VL) the frequency 15,40 GHz is the highest one. This fact is in accordance with practice and literature, so the respective value was used for evaluated the follow results.
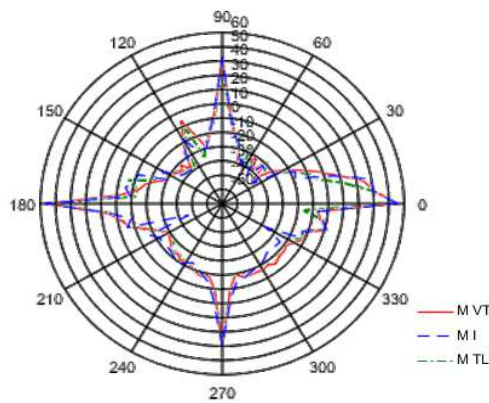
Figure 10: Radar signature for M_VT aircraft model.

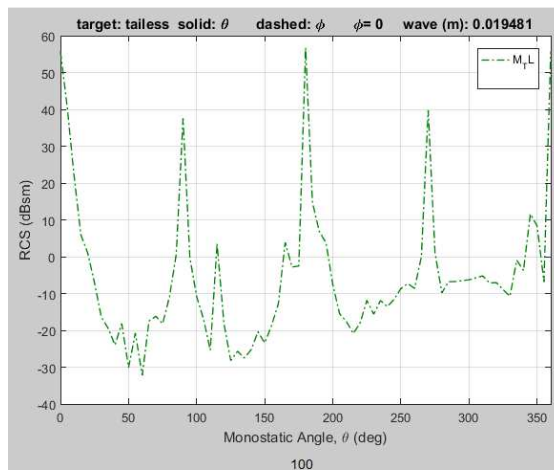

Figure 11: Radar signature for M_I aircraft model.

Figure 12: Radar signature for M_TL aircraft model.

When we compare the three targets with the Fig. 13, we have two main conclusions: (1) the 3D aircraft's designs have similar radar signature; (2) we can infer that the M_I model (blue line) is the one with low signature.
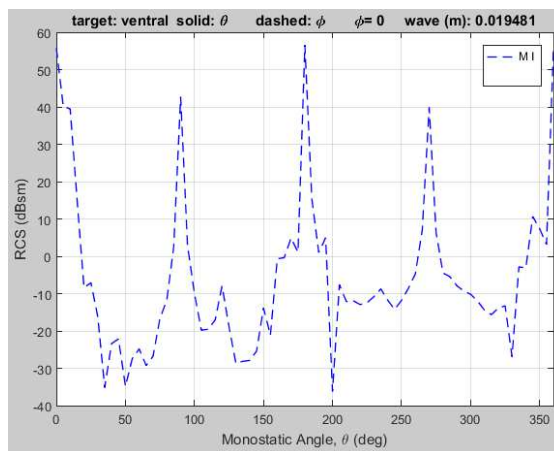
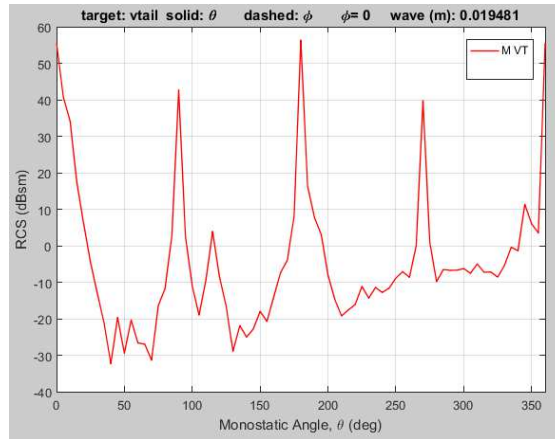**Figure 13: Radar signature for the M_VT, M_I and M_TL aircrafts designs.**

The supposition confirmation is based on the analysis results shown on the RCS linear plot (Figures 14, 15 and 16).Figures 14, 15 and 16 graphics clearly have four main peaks. Two of them are mainly reflections caused in the end-region scattering (0° and 180°). However there's a spike pointed at the front (270°) sector, a typical undesirable situation.

Figure14: RCS of M_TL aircraft design at 15,40 GHz.

Figure15: RCS of M_I aircraft design at 15,40 GHz.

Figure 16: RCS of M_VT aircraft design at 15,40 GHz.

It was extracted points every 5° to calculate an average in each aircraft´s region (sides, back and front). This calculation is summarized in Table 6. Crossing the results of the Table 6 with the measured areas below each linear plot (Figures 12, 13 and 14) it was concluded that ventral intake with V (M_I) stabilizer is the prototype with the best signature.

Model	Sides [dBsm]	Back [dBsm]	Front [dBsm]
M_TL	11,01	-9,59	-3,46
M_I	11,64	-10,42	-2,70
M_VT	14,67	-8,38	-6,25

Table 6: Aircraft´s radar signature averages.

Finally for the M_I geometry there's a peak of visibility in 56.58dBsm and a respective minimum in -36.18dBsm. For that configuration the average of visibility of the target is 0,89 m².

CONCLUSION

In the present research a supersonic aircraft is conceptually designed. Its stealth-aerodynamic characteristics are analyzed. Using the physical optics to study the RCS characteristics and based on wave drag simulations generated in SOM this paper composed several body configuration sets for analysis of the stealth-aerodynamic characteristics. There are three main conclusions: (1) aerodynamic property is essential parameter for stability and controllability of an aircraft. For this reason the decision in shaping must be coupled with stealth design;(2) the Radar Cross Section is the measure of targets' to radar. It is correlated with high frequencies and planform shaping; (3) the design rule for a stealth aircraft is an optimum equilibrium of stealth-aerodynamics characteristics. This study allows observing, in accordance with the literature, that the best design for stealth characteristics is not the best for the aerodynamics ones. The effort to study and develop optimization tools to enable reaching the best result as possible for both characteristics is fundamental since usually is not that intuitive and not that obvious.

Finally the conclusions provide some reference for stealth aircraft's conceptual design and aerodynamic analysis.

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