Radar Cross Section Reduction using Characteristic Mode Analysis

Marcelo Bender Perotoni [1], Felipe A. A. da Silva [1], Kenedy Marconi G. dos Santos [2], and Danilo Brito Almeida [2]

[1] UFABC
Santo Andre, SP,09210-580, Brazil
Marcelo.perotoni@ufabc.edu.br

[2] IFBA
Vitória da Conquista, BA, 45078-900, Brazil
kenedymarconi@gmail.com

Abstract **─** This article covers the application of Characteristic Mode Analysis to reduce the Radar Cross Section of a canonical object, a metallic cylinder. Electrically small, non-resonant slots are added to the structure and loaded with complex impedances, positioned on hot spots found after mode analysis based on the Method of Moments. Two critical frequencies with higher amplitude radar cross-section, 400 and 450 MHz, were analyzed. Results showed monostatic reductions on average of 5 dB, in both frequencies for two different sets of loads and at two different incident angles. Radar cross-section patterns were found to be affected by the load impedances, thereby offering a low profile and low drag solution to control the backscattering signature pattern.

Index Terms **─** Characteristic-mode analysis, electromagnetic simulation, radar cross section reduction.

I. INTRODUCTION

Reduction of the RCS (Radar Cross Section) of an aircraft can increase the survivability rate in combat cases since its detection becomes more difficult due to the reduced energy reflected back to the radar antenna. That means the enemy detection can only occur when the aircraft is deep into the enemy lines, which can be a game-changer in the context of aerial dominance. Conversely, for small civilian boats and ships, metallic structures based on corner reflectors help increase the RCS response so that they become more visible in operation [1], which renders their operation safer. When the incoming wave hits the target, the total energy is scattered in multiple directions and partially converted in heat, the echo is the part the hits back the radar. Given the fact that the echo response is related to the aircraft type, it is sometimes called its signature [2]. The scattering response of an aircraft depends on its geometry and its materials, as well as the incoming wave characteristics (polarization, frequency) [3]. Several different approaches are commonly used to reduce the RCS in aircraft, notably on the design of stealthy vehicles [4], which have lower amplitude backscattered responses than those expected from their actual dimensions. Extensive use of electromagnetic simulation allows the test of alternative geometries (a practice also known as shaping) which scatter back the incoming energy in directions other than that of the incoming wave [5]. Another technique involves radar absorbing materials (RAM), specifically designed to operate within radar frequency ranges, coating parts of the vehicles that are responsible for the high scattering (hot spots). A specific RAM case designed to operate within the X-band (10 to 12 GHz) was proved to reduce the RCS response in the average of 10 dB on a modified F5 fighter, analyzed by means of electromagnetic simulation [6]. Metamaterials (artificially engineered materials) are usually employed to reduce the RCS of antennas, which in virtue of their resonant nature can be responsible for a large part of the backscatter energy. For instance, artificial magnetic materials (AMC) were imprinted on a patch antenna as a kind of load, so that the overall RCS is reduced, within the band of 9.66 GHz to 11.50 GHz [7]. Another investigation had two AMC arrays operating in overlapped frequency ranges, mounted in a chessboard fashion, operating in the frequency range of 5.8 GHz [8]. Another chessboard-like structure, made out of a matrix of copper and high-permittivity dielectric material enabled the control of RCS for the frequency of 18.45 GHz, achieving reductions around 15 to 30 dB [9]. The use of plasma as an electromagnetic shield has also been proposed as a means to achieve RCS reduction, shown in one example at the 10 GHz range, simulated with an FDTD (Finite Difference Time Domain) code [10]. Other techniques to achieve a stealthy operation worth

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mention are passive and active cancellation [4],[11], the latter relying on heavy high-speed data processing and phased arrays. This article covers the RCS analysis of a canonical structure, a metallic cylinder, and investigate the impact of small loaded slots on its response at two different close frequencies (400 and 450 MHz). The impact on the RCS is analyzed using computer simulation, based on the CMA (Characteristic Mode Analysis). The proposed technique, without the use of shaping and/or RAM, achieves a reduction and modification on the RCS signature. Due to its structural nature it can be made switchable, enabling a dynamical modification of the electromagnetic response and therefore turning the target detection and identification more complicated. Placement of inductive loadings on locations found after a CMA analysis was a way devised to reduce unwanted out of band antenna coupling, a similar approach to a different goal observed in this study [12].

II. RCS EVALUATION

A hollow metallic cylinder (1 meter long and with a radius of 0.2 m, zero thickness), made of PEC (perfect electric conductor) is analyzed according to Fig. 1. The worst case scenario in terms of radar signature, i.e., a plane wave with its electric field parallel to the cylinder axis is modeled with FEKO MoM (Method of Moments) solver. MoM offers good advantages for the simulation of metallic structures, given the fact the mesh is done only on the surface, in contrast to volumetric meshes of Finite Element Method (FEM) or Finite-difference Time-domain (FDTD). The MoM impedance matrix is also the basis for the CMA computation, therefore this numerical method is directly tied to the characteristic modes computation [13]. For simulation of a real object, more complicated than the present canonical cylinder, the Multi-Level Fast Multipole Method (MLFMM) can be used to reduce the coupling on the MoM matrix and turn the matrix sparse, easing the numerical solution. The cylinder monostatic radar response is simulated and the results with the frequency swept from 200 MHz to 700 MHz are shown in Fig. 2, for the angle Θ=90° - angle whose response is the largest in terms of backscattered energy.

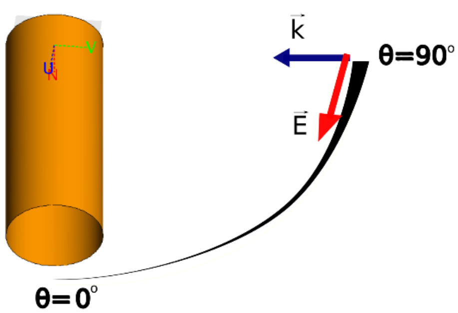

Fig. 1. Simulation setup.

It can be seen from Fig. 2 that the range around 400-450 MHz has the largest return amplitude, the respective surface current distributions are shown in Fig. 3. The surface current absolute values refer to a plane wave whose absolute amplitude is 1 V/m, constant over the entire frequency range, default within the FEKO suite.

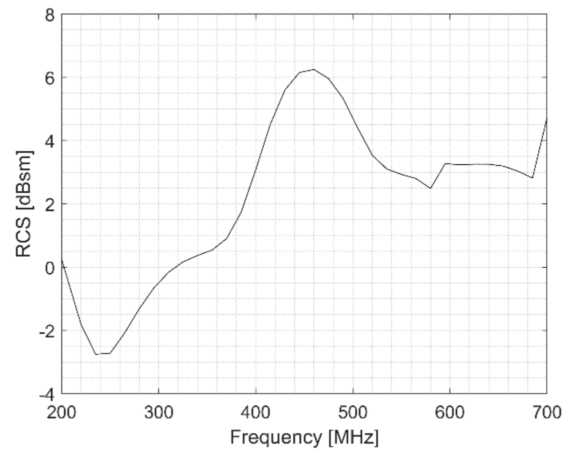

Fig. 2. Simulated RCS for the angle Θ=90°.

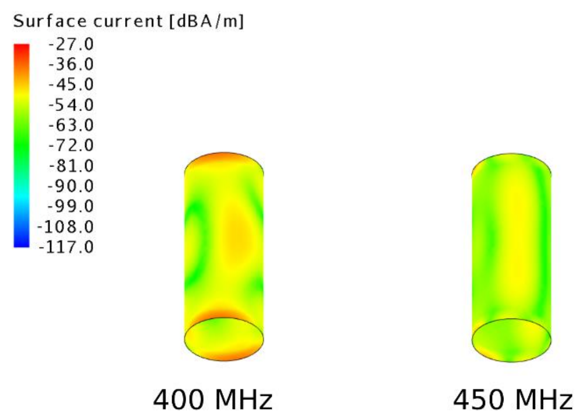

Fig. 3. Surface currents distribution for two different frequencies, incident angle Θ=90°.

From the current distribution at 400 MHz and 450 MHz it is possible to see that the area around the cylinder edges concentrates their maximum amplitudes, therefore they are backscattering hot spots. These areas should be possible options for having a RAM coating. This particular frequency range (C-band) is used by Early Warning Radars, for long-range detection, and each one of the two individual frequencies will be dealt with individually. The range resolution parameter of the target depends on the frequency span of the incoming signal, whereas the cross-range resolution depends on different angles scattered from the object [14]. Both domains – frequency and angular range, are therefore covered in the study.

III. CHARACTERISTIC MODE ANALYSIS

Characteristic Mode Analysis computes the natural modes on a metallic structure, described in terms of eigenvalues λ_n. A set of orthogonal current modes is found, and the individual modes existence and respective weight on the final current shape depend upon their individual excitation. Some modes might be good radiators in some frequencies whereas others might only store reactive energy. This analysis has been used as a tool for antenna placement, taking advantage of the natural resonant modes of chassis of vehicle or mobile phones to achieve better performances [15]. There is also a relation between CMA and the RCS of a metallic structure [16] – the RCS can be computed as the summation of all characteristic modes inside a structure [17]. An application involved a computer model of a jet aircraft, that in simulation showed a reduction in the RCS response by loading it with resonant antennas positioned in hot spots pointed out by a CMA study [13] - the antennas dissipated in their loads the high intensity currents generated by the plane wave excitation, thereby reducing the backscattering energy.

Several different parameters related to the eigenvalues describe their relative importance on the electromagnetic response of the structure, one of them is the Modal Significance (MS), that represents the normalized amplitude of the current modes. MS depends only on the shape and size of the structure, without influence on the excitation [18]. Figure 4 shows the computed MS for the three first modes of the cylinder – MS values closer to one indicate that the mode resonates. For the frequency range close to 400 MHz the mode 2 has the largest importance, whereas 450 MHz has mode 4 as the most significant. It can be seen in Fig. 5 that these modes have a current surface pattern similar to the one generated after a plane wave illumination. It indicates that the frontal illumination from a plane wave excites currents that accommodate/resonate in these specific modes, a scenario that reproduces the radar illuminated target.

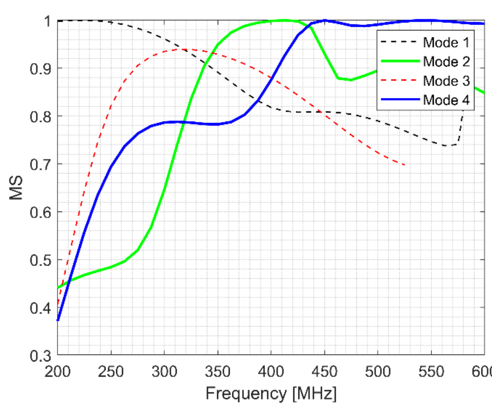

Fig. 4. Computed modal significance for the three first modes. Bold/solid lines represent the modes responsible for the large RCS values.

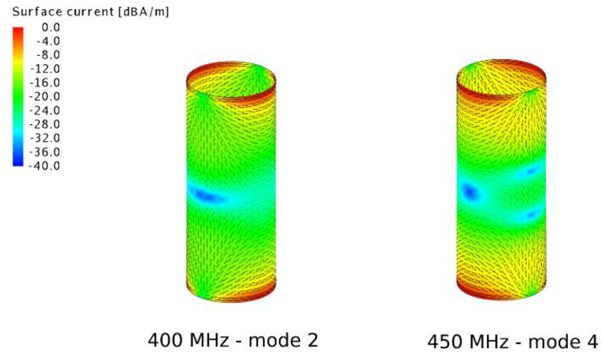

Fig. 5. Normalized current distribution relative to the modes at frequencies 400 MHz and 450 MHz.

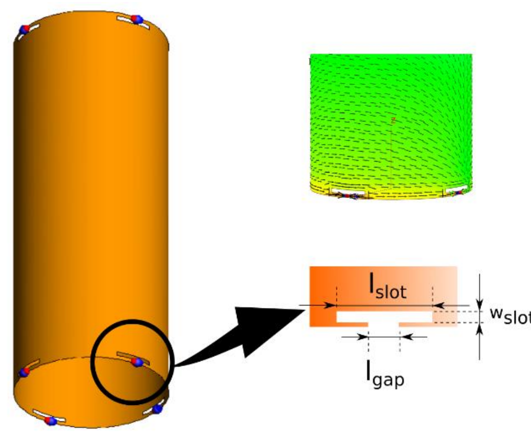

Fig. 6. Slots geometry and detail of the developed current surface shape (top right), excited by the ports (blue/red dots in the zoomed area). The dimensions are l_{slot}=10 cm, w_{slot} = 1 cm and l_{gap}=1.16 cm.

Once CMA provides an indication of which frequencies are more likely to radiate the next step consists of the proper selective excitation of these modes. Two basic formats are offered in the literature [19],[20], capacitive and inductive. The first uses a metallic patch placed where the mode has a current minimum; the latter has a loop where the mode current peaks, both are supposed to be electrically small, acting as a coupling to the source so that the large structure itself radiates. It is worth mentioning that these coupling structures are not necessarily matched, in general, due to their small electrical dimensions they have large imaginary parts which need to be dealt with in case of matched antennas or systems (50 Ω). In regard to the choice between capacitive or inductive excitation, since the interest is in a flying object, due to aerodynamic constraints a loop excitation was chosen – an electrical patch floating above the cylinder would induce an aerodynamic drag and the loop, being of a slot type, does not impose this sort of constraint. The main idea consists in directing the incoming plane wave energy into the slots so that it is dissipated by the loads and/or scattered in other directions, in order to reduce the monostatic backscatter energy. The chosen excitation is depicted in Fig. 6. A total of eight symmetrical slots were distributed along the edges of the cylinder, to capture both 2nd and 4th modes, depending on the direction of the plane wave excitation. The input impedance at the gap is approximately 20 + j350 Ω (400 MHz) and 60 + j434 Ω (450 MHz).

IV. RCS REDUCTION

Complex impedances ($Z_{slot} = R_{slot} + jX_{slot}$) were added as loads to each one of the slots, and it was evaluated their influence on the RCS response. Figure 7 shows the RCS response (direction Θ=90°) for different values of Z_{slot}, for both 400 MHz and 450 MHz. It can be seen that the optimum real part (R_{slot}) is close to a short whereas the optimum X_{slot} is larger for the case of 450 MHz than that of 400 MHz, and also that the set of possible load values that decrease the RCS is larger for the higher frequency than to the lower one. In terms of load type, a capacitive part should be added to achieve lower RCS values for both individual frequencies. It was observed a strong sensitivity on the RCS signature on the Z_{slot} value, suggesting a possible means of scrambling radar detection by means of emulating targets with different PDFs (Probability Density Function) and reconstructed SAR/ISAR images [21]. Electronically switching of different loads can be implemented dynamically as an incoming radar signal is detected in case of evasive or stealthy operations. The size and relative position of the slots were not seen to have a large influence on the RCS reduction, given their small electrical size.

In terms of spatial angular responses, two particular sets of optimized Z_{slot} values, $Z_{slot}1$= (0.1 - j240) Ω and $Z_{slot}2$ = (0.1 - j330) Ω are shown in a polar plot format, Fig. 8, alongside with the baseline (no slots) case. The angle 90° had reductions of 4.2 dB (for $Z_{slot}1$, 400 MHz) and 3.3 dB (with $Z_{slot}2$, 450 MHz). The 0° direction had a reduction of 9.4 dB (400 MHz) and 4.2 dB (450 MHz), both with the $Z_{slot}2$ load impedance. The cut slots represented only 0.7% of the total cylinder area, so they do not impose a large modification on the original structure given the small electrical size of the exciters.

Figure 9 shows the PDF for the original and modified cylinder, with the two sets of impedances Z_{slot}. It can be seen that the inclusion of slots and the respective impedances modify the statistical distribution of the backscatter energy. For the case of $Z_{slot}2$ it shifts the distribution towards smaller RCS values. $Z_{slot}1$ minimizes the RCS for 400 MHz but the PDF still resembles the original object without slots whereas $Z_{slot}2$ provides a more substantial modification on the shape of the PDF function, for both frequencies. This modification turns the vehicle detection more difficult given that the PDF acts as a sort of electromagnetic signature.

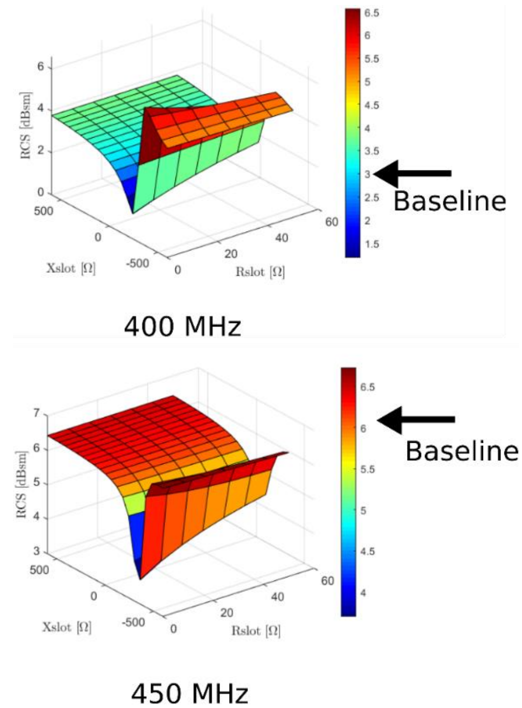

Fig. 7. Simulated monostatic RCS (Θ=90°) for 400 MHz and 450 MHz, with different loads connected to the slots. The baseline original RCS, without the slots, is shown in the black arrows by the colorbars.

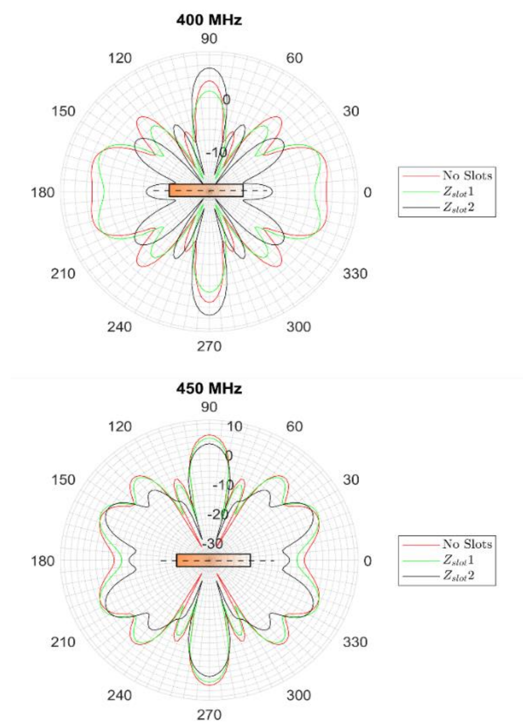

Fig. 8. Simulated monostatic RCS, in dBsm. Angle Θ swept, with the cylinder left for reference on the center of the figures.

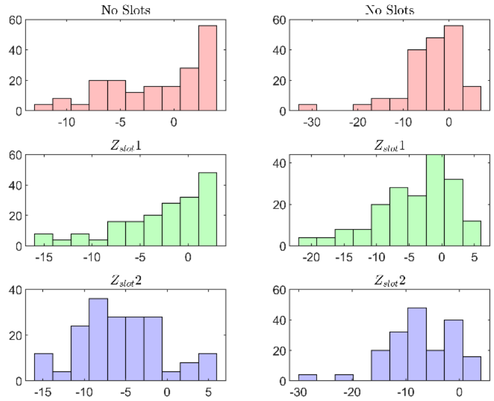

Fig. 9. Probability Density Functions for 400 MHz (left column) and 450 MHz (right column).

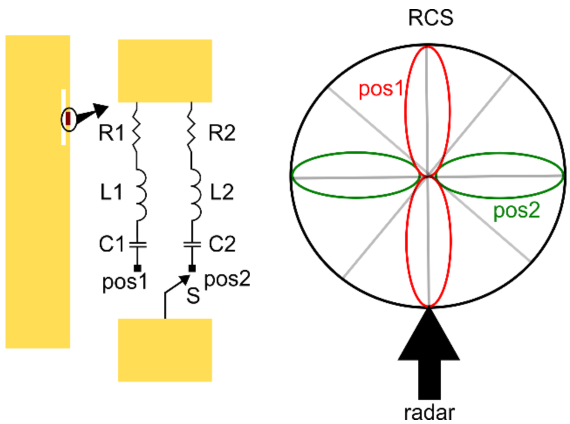

Fig. 10. Description of the switching load approach. Polar plot shows an example only, not related to this work.

The procedure for achieving the CMA reduction of the RCS can then be synthesized is as follows:

1. Determine the frequencies of interest. It can be VHF or low UHF for Early Warning Systems or X band for missile and aircraft radars, for instance.
2. Find out within the specific frequency range the most significant modes, running a CMA evaluation.
3. For these modes, investigate their current distribution pattern.
4. On the found hot spots (high amplitude surface current) deploy non-resonant slots, and add complex loads to them. The initial estimate of the load impedance should be the conjugate input impedance of the slot, at the frequency of interest. Alternatively, capacitive patches can be used as exciters, but these should instead be placed on points where the modes present maximum voltages.
5. Run a plane wave excitation and evaluate the RCS response after a sweep on the load impedance. Optimum load impedances can be chosen as a compromise between different frequencies, or as a way to create a different RCS signature.

Dynamic switching of the loads allows the on-the-fly electromagnetic signature scrambling, as Fig. 10 shows. The radar is positioned as shown on the polar plot, and it detects the target at the maximum backscatter direction. Upon switching the load from position S1 to S2 the main lobe moves to another direction, scrambling the proper vehicle detection.

V. CONCLUSION

This article covered the use of CMA analysis of a metallic cylinder and the respective loading of the excited modes in order to modify its RCS signature. Without traditional RCS reduction techniques, like absorbing materials or shaping, this technique changes the RCS of a canonical object with minimal structural modifications, given the fact the slots are electrically small and do not introduce aerodynamic drag to an aircraft. It also enables the modification to be implemented dynamically, by switching different sets of loads. Moderate RCS reductions (around 5 dB) were found after numerical simulations.

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Marcelo B. Perotoni Electrical Engineer (UFRGS, Porto Alegre, Brazil), Ms.C. and Ph.D. in Electrical Engineering from USP (Sao Paulo, Brazil). He has been involved with electromagnetic simulation, RF and EMC since 2002. He is currently a professor at UFABC.

Felipe A. A. da Silva Electronic Technician and Bachelor in Science and Technology, currently in the Information Engineering program at UFABC. He was a visiting student at Montana Tech and has interests in Propagation and RF design.

Kenedy Marconi G. dos Santos is B.Sc. in Electrical Engineering (2006) – PUC MG, M.Sc. in Electrical Engineering (2011)-UFMG, Ph.D. in Electrical Engineering (2018) – UFBA. Currently is professor at the IFBA. He has experience in Electrical Engineering with emphasis on EMC, Microwave and Antennas.

Danilo B. Almeida is B.Sc. in Electrical Engineering (2005) – UNIP – SP. He is a Specialist in Occupational Safety and Energy Efficiency. Currently is professor at the IFBA and FAINOR.