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Numerical and experimental methods for electromagnetic measurements in plasmas

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Abstract

It has been noticed that plasma with different characteristics could provide distinct response to electromagnetic waves, i.e. could reflect or absorb them. The Flight Mechanics Group at DRDC Valcartier is leading a Technology Investment Fund (TIF 11az) research project aiming to improve understanding on the interactions between plasma and electromagnetic waves.

Plasma actuators are receiving significant research attention in aerodynamic applications. Associated with these plasmas is the potential to change a vehicle's radar cross section (RCS). This study examined the open literature in order to identify the plasma parameters affecting RCS as well as investigating published experimental and numerical modeling methods to evaluate the plasma effect. Recommendations for future work are presented including the use of static magnetic fields to modify the plasma.

Résumé

Il a été remarqué que plasmas avec caractéristiques différentes pourraient fournir des réponses distinctes aux ondes électromagnétiques, c'est à dire pourrait les refléter ou les absorber. Le Groupe Mécanique du vol à RDDC Valcartier est à la tête d'un projet de recherche dans le cadre du Fonds d'investissement technologique (FIT 11az), qui vise à améliorer la compréhension sur les interactions entre le plasma et les ondes électromagnétiques.

Actionneurs plasma bénéficient d'une attention important sur les applications dans le domaine de l'aérodynamique. Ces plasmas sont associés aux potentiels de modification de la signature radar des véhicules. Cette étude a examiné la littérature ouverte afin d'identifier les paramètres du plasma que affectant la réduction de la signature radar, ainsi que les méthodes de modélisation expérimentale et numérique pour évaluer l'effet du plasma sur les ondes électromagnétiques. Recommandations pour les travaux futurs sont présentées, y compris l'utilisation de champs magnétiques statiques pour la modification du plasma.

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Executive summary

Numerical and experimental methods for electromagnetic measurements in plasmas

F. Mirhosseini; B. Colpitts; DRDC Valcartier CR 2012-058; Defence R&D Canada – Valcartier; April 2012.

Introduction or background: Plasma actuators offer promising opportunities for flow control because of their fast response and no moving parts. Through a comprehensive study of the open literature we investigated the influence of plasma actuators on radar cross section (RCS). Specifically the relevant plasma properties to modify RCS are identified along with experimental methods that have been used to determine both plasma properties and target RCS. Finally the most promising numerical methods to represent the RCS of the plasma actuator are identified.

Results: The most significant properties of the plasma in terms of RCS are the plasma frequency, primarily governed by the electron density and the plasma pressure. The plasma pressure directly influences the electron lifetime and collision rate which is linked to the electron temperature. Adding a magnetic field to the plasma introduces the electron gyro-frequency which can be used to further control the plasma properties. Conventional methods for RCS measurement are applicable to plasma actuators along with reflectometry measurements to determine specific properties of the plasma such as the plasma frequency. Numerical modelling of the plasma as it relates to RCS offers opportunity to explore numerous configurations without the time and expense of establishing experimental setups. The finite-difference time-domain (FDTD) method appears to be most utilized for modelling the interaction of electromagnetic waves and plasma.

Significance: Properly configured plasma can act as radar absorbing material although initial studies of the very thin layer of plasma associated with certain actuators show it has little influence on RCS. Therefore, the ability to both numerically model and measure the RCS of numerous actuator designs is a cost effective approach to assess the feasibility of plasma actuators for RCS management of vehicles.

Future plans: Experimental measurements on DBD plasma actuator’s effect on RCS in low pressure and non-stationary conditions can be done. Wind tunnel tests could be done to measure the effect of speed and low pressure which increase electron lifetime and potentially generates a plume. To estimate the impact of object speed and air pressure on RCS, simulation can be done by using a numerical technique such as the FDTD. The effect of magnetic fields on the plasma opens a new dimension of opportunities along with considerable complexity in modelling. These effects can be investigated by both numerical and experimental techniques.

Sommaire

Numerical and experimental methods for electromagnetic measurements in plasmas

F. Mirhosseini; B. Colpitts ; DRDC Valcartier CR 2012-058 ; R & D pour la défense Canada – Valcartier; avril 2012.

Introduction ou contexte : Actionneurs plasma du type Décharge à barrière diélectrique (DBD) offrent des perspectives prometteuses pour le contrôle de l'écoulement en raison de leur réponse rapide et l'absence de pièces mobiles. Une étude approfondie dans la littérature ouverte a été fait pour se connaître l'influence des actionneurs plasmas sur la réduction de la signature radar de véhicules. Plus précisément, les propriétés du plasma qui affectent la signature radar sont identifiées, ainsi que les méthodes expérimentales le plus pertinentes pour déterminer ces propriétés du plasma. Enfin, les méthodes numériques les plus prometteuses pour la modélisation de la signature radar des actionneurs plasmas sont identifiées

Résultats : Les propriétés les plus importantes du plasma en termes de signature radar sont la fréquence du plasma, principalement régie par la densité électronique et la pression du plasma. La pression du plasma influe directement sur les taux de collision des électrons et la durée de vie qui est liée à la température des électrons. L'ajout d'un champ magnétique dans le plasma ira introduire la gyrofréquence électronique qui peut être utilisé pour contrôler les propriétés du plasma. Les méthodes conventionnelles pour mesurer la signature radar sont applicables aux actionneurs plasma ainsi que des mesures de réflectométrie pour déterminer les propriétés spécifiques du plasma telles que sa fréquence. La modélisation numérique du plasma apporte la possibilité d'explorer plus rapidement des différentes configurations sans le besoin des montages expérimentaux qui sont normalement plus coûteuses. La méthode des différences finies dans le domaine temporel (FDTD) apparaît dans la plupart des modélisations des interactions des ondes électromagnétiques avec le plasma, dans la littérature ouverte.

Importance: Une fois configuré correctement, le plasma peut agir comme un matériel absorbant des ondes radar, bien que des études initiales aient montré que la couche très mince de plasma associé à certains actionneurs a peu d'influence sur la signature radar. Pourtant, une capacité numérique ainsi que expérimental pour mesurer la signature radar des différents concepts d'actionneurs plasma est une approche rentable pour évaluer la faisabilité de ces actionneurs sur la modification de la signature radar de véhicules.

Perspectives: Des mesures expérimentales dans des conditions non-stationnaires à basse pression peuvent être faites pour vérifier l'effet des actionneurs plasma du type DBD sur la signature radar. Des essais en soufflerie peuvent être aussi utilisé pour mesurer l'effet de la vitesse et de la pression, qui affectent la durée de vie des électrons et qui peuvent potentiellement générer un panache. Pour estimer l'impact de la vitesse de l'objet et la pression de l'air sur la signature radar, la simulation peut être faite en utilisant une technique numérique comme la FDTD. L'effet des champs magnétiques sur le plasma augment considérablement la complexité et ouvre des nouveaux défis. Ces effets peuvent être étudiés par les deux techniques numériques et expérimentales.

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1 Introduction

Plasma actuators for aerodynamic applications are receiving significant research attention and it is necessary to know the effects of this plasma on the vehicle radar cross section (RCS). This initial study identifies the critical parameters affecting the RCS of plasma along with a literature review of both the experimental techniques and numerical techniques for determining the effects of plasma on RCS. A brief section of recommendations for future work is also given.

Through an extensive literature search and study we have identified that there are many parameters affecting the RCS or reflection from a layer of plasma. These parameters along with methods of plasma generation are discussed in Section 1.

Plasma has a capability that its refractive index can be controlled by changing parameters such as the electron density profile, so the RCS becomes controllable. From the various methods of plasma generation, the Dielectric Barrier Discharge (DBD) actuator has shown benefits like aerodynamic drag reduction noticed in the last decade [1]. In Section 2, different techniques for RCS measurement in plasma and the benefits and drawbacks of each one are addressed.

Since it is difficult to physically generate plasma in complex profiles, particularly on structures with complicated geometries like an aircraft surface, many simulation and numerical methods have been developed to accomplish this. These numerical methods are discussed in Section 3 while in Section 4 there will be recommendations for future work.

2 Plasma parameters affecting RCS

2.1 What is plasma?

Plasma is a state of matter in which the negative ions or electrons and positive ions are available at the same time. In fact plasma is a quasi-neutral mix of electrons, ions and neutral particles. Not all plasmas are fully ionized and the percentage of ionization depends on the application for which plasma is generated. These applications vary widely from plasma TV to plasma antennas and plasma stealth technology.

Plasmas can be generated in different temperatures from close to zero Kelvin to higher than 10 GKelvin, so the plasma can be classified as hot or cold. In hot plasma there is a thermodynamic state which is called Local Thermodynamic Equilibrium (LTE). This sate is characterized by the property that all particle concentrations are only a function of temperature. This plasma is sometimes called thermal plasma. Cold plasmas, on the other hand, are characterized by the property that the energy is selectively fed to the electrons, so the electron temperatures can be considerably higher than the heavy particles in the plasma. This kind of plasma is called the non-equilibrium or non-LTE plasma and has the typical properties such as electrical conductivity, light emission and chemical activity. Cold plasma is the type of plasma used for many applications including plasma stealth [2] and dielectric barrier discharge plasma is also in this category of non-thermal or cold plasma [3].

Plasma can be magnetized or un-magnetized depending on the application for which it is generated. Magnetized plasma is achieved by applying a DC or AC magnetic field. Since electrons oscillate in magnetic fields, there is an increase in the collision rate which is beneficial for some applications like plasma stealth and RCS reduction [3]. An electromagnetic wave in plasma has a magnetic field in which electrons oscillate. In un-magnetized plasma these electron waves or oscillations are related to the incident wave, but in magnetized plasma the electron waves have four modes. Modes O (Ordinary) and X (eXtraordinary) which are perpendicular to the external magnetic field and R (Right-hand circularly polarized) and L (Left-hand circularly polarized) which are parallel to the field. For O-mode the dispersion relation and cut-off frequency is the same as un-magnetized plasma shown in equation (2), but for the other three modes the dispersion relation is more complicated. In plasma actuators we will restrict our investigation to the un-magnetized case [4].

2.2 What is plasma stealth?

Plasma stealth is a proposed process to use ionized gas (plasma) to reduce the Radar Cross Section (RCS) of an airframe or ground-based equipment [5], [6]. There is always an interaction between the incident electromagnetic wave and ionized gas. These interactions have been extensively studied for many purposes, including concealing aircraft from radar as in stealth technology.

Various methods might plausibly be able to form a layer or cloud of plasma around a vehicle or an object to deflect or absorb radar, from simple electrostatic or Radio Frequency (RF) discharges to more complex laser discharges. It is theoretically possible to reduce RCS in this way, but it may be very difficult to do so in practice. Generally, the techniques of plasma generation can be divided in two methods Electric Discharges (DC, RF or Microwave Discharges) and Beam Discharges (Electron Beam or Laser Beam Discharges). The DC discharge is itself divided to pulsed and continuously operated discharges and RF is also divided to capacitively and inductively induced discharges [3].

Each of the various plasma sources discussed above has its own peculiarities, advantages, and disadvantages. The choice of the proper source for the specific task requires the study of the characteristics of the various plasmas. We can only give a brief summary of the various plasma sources. The DC discharge has the advantage that the microscopic processes are rather well known and understood and that such plasmas can be understood in great detail. Interior electrodes are required and the possibility of reactions with reactive and corrosive gases must be considered in certain applications. The ion energy at the cathode is usually comparatively high. Power sources are well developed and widely available.

By contrast, RF discharges can operate with insulated or external electrodes. They can be electrode-less. Therefore, reactive processes with metal electrodes can be avoided. The lifetime of devices with electrode-less RF discharges is long. RF sources can be operated over a wide range of pressures. Low gas pressure is possible in discharges using magnetic fields (helicon discharges). The ion energy can be controlled over a wide range. The microscopic processes in RF discharges are rather complex [3]. Diagnostic tools are well developed, but sometimes difficult to use due to interference by the RF sustaining voltage. Microwave discharges also operate without electrodes. Plasmas of high density can be generated in the pressure range from 10 Pa up to atmospheric pressures. The plasma excitation at very low pressures (less 1 Pa) is effective in microwave-excited and magnetic-field-supported ECR (Electron Cyclotron Resonance) discharges. The ion energy in the microwave plasma is generally low and can be controlled by additional DC fields or an RF bias voltage. Suitable power supplies are readily available.

Plasma generation in the low-pressure range (<100 Pa) by electron beams involves more complicated beam sources. The shape of the plasma may by controlled by the shape of the exciting beam. The dielectric barrier discharge (DBD) operates at or near atmospheric pressure. The plasma that is produced is highly non-thermal. Various applications in the area of surface treatment, cleaning, and modification are feasible, because no vacuum environment is required. Plasma sources are usually operated with static electric or alternating electromagnetic fields. An additional static magnetic field performs two tasks. Firstly, the plasma confinement is enhanced by limiting the diffusion of charged particles perpendicular to the magnetic field. Secondly, the power absorption is enhanced by increasing the electron–neutral collision rate due to the longer trajectories of the electrons in the plasma at low pressures, so lower RCS is achieved [3]. The magnetic fields also open new absorption channels, caused by, for example, ECR resonances or helicon waves. The installation of static magnetic fields can be inexpensive, if permanent magnets are used.

2.3 Plasma parameters that affect RCS

2.3.1 Plasma frequency

This parameter (ω_{pe}) defines the cut-off frequency at which the waves are reflected from plasma, that is, frequencies below ω_{pe} will propagate while frequencies above ω_{pe} will be reflected. In a cold plasma approximation the plasma frequency can be related to wave number as in equation

(1). In this equation ω is the incident wave frequency, c is the speed of light in a vacuum and k is the wave number.

$$\omega^2 = \omega_{pe}^2 + c^2k^2 \quad (1)$$

It can be seen that $k = 0$, when $\omega = \omega_{pe}$, so at the cut-off frequency propagation ceases and reflections occur.

2.3.2 Electron density

The electron density n_e is a parameter that defines the plasma frequency. They are related by equation (2).

$$\omega_{pe} = \sqrt{\frac{n_e e^2}{\varepsilon_0 m_e}} \quad (2)$$

Here e and m_e are the electron charge and mass respectively, and ε_0 is the permittivity of vacuum. There are some methods to measure electron density and plasma frequency. The most widely used techniques are reflectometry [7], [8] and interferometry [9] both are based on the same principles.

In reflectometry, ω_{pe} is measured based on a transition in the reflected wave power and then by using equation (2) the n_e can be calculated indirectly. In reflectometry, ω_{pe} is measured based on a transition in the reflected wave power and then by using equation (2) the n_e can be calculated indirectly.

In interferometry, the attenuation rate (α) and phase shift (β) between the incident wave and transmitted waves are measured then by using equation (3), (4) and (5) the plasma frequency and electron density can be calculated. If we define the real part and imaginary part of ε_r as (ε_r') and (ε_r''), we can define (α) and (β) as in equations (4) and (5).

$$\varepsilon_r = 1 - \frac{\omega_{pe}^2}{\omega(\omega - jv)} = 1 - \frac{\omega_{pe}^2}{\omega^2 + v^2} - \frac{v}{\omega}\frac{\omega_{pe}^2}{\omega^2 + v^2} j = \varepsilon_r' - \varepsilon_r'' \quad (3)$$

$$\alpha = K_0 \left\{\frac{1}{2}\left[-\varepsilon_r' + (\varepsilon_r'^2 + \varepsilon_r''^2)^{1/2}\right]\right\}^{1/2} \quad (4)$$

$$\beta = K_0 \left\{\frac{1}{2}\left[\varepsilon_r' + (\varepsilon_r'^2 + \varepsilon_r''^2)^{1/2}\right]\right\}^{1/2} \quad (5)$$

Here, K_0 is the wave number in vacuum.

2.3.3 Collision rate

Collision rate or collision frequency (v) shows the average collision probability between neutral particles and electrons in plasma. The collision rate and electron temperature are related as shown in equation (6).

$$v = n_0 \left(\frac{2kT_e}{m_e}\right)^{1/2} \sigma_0 \tag{6}$$

Here T_e is the electron temperature, σ_0 is the electron-neutral collision cross section, and, n_0 is the neutral particle density. For RCS reduction by electromagnetic absorption, a plasma with high collision rate and low electron density is needed [10], [11].

2.3.4 Electron temperature

The electron temperature shows the electron kinetic energy. It can be measured by interferometry indirectly by determining the collision frequency and using equation (6). As it is explained for measuring electron density, by interferometry we can measure attenuation and phase shift and then calculate plasma and collision frequency. By having collision frequency, we can calculate electron temperature. Electron Temperature can also be measured by spectroscopy [12].

In some experiments the Longmuir probe is used to measure electron temperature and electron density [13]. Langmuir probe is a fine metal wire which is used to investigate the plasma. It has a characteristic voltage-current curve based on which the plasma parameters can be measured.

2.3.5 Plasma pressure

The plasma pressure is the pressure of the medium gas and an increase in pressure increases the collision rate and decreases the electron lifetime [6], [14].

2.3.6 Electron lifetime

The electron lifetime is the average time an electron is separated from an atom to the time it is recombined again to a generated positive ion [14].

2.3.7 Electron gyro-frequency

It is the frequency by which electrons go in a circular path whose plane of motion is perpendicular to the applied magnetic field in magnetized plasma. The gyro-frequency is called the cyclotron frequency in some references [14].

$$\Omega = \frac{eB}{m_e c} = 1.76 \text{ x } 10^7 B \; rad/s \tag{7}$$

Here, B is the applied magnetic field.

2.3.8 Dielectric constant

Dielectric constant is different for un-magnetized and magnetized plasma and is a complex number. The real part and imaginary part which determine the attenuation rate and phase shift of the wave propagated in plasma. This number is related to the parameters described above. The dielectric constant of un-magnetized and magnetized plasma are shown in equations (3) and (8).

$$\varepsilon_r = \frac{\frac{\omega_{pe}^2}{\omega^2}}{\left[1 - j\frac{v}{\omega} - \frac{\frac{\Omega^2}{\omega^2}(sin\theta)^2}{2\left(1 - \frac{\omega_{pe}^2}{\omega^2} - j\frac{v}{\omega}\right)}\right] \pm \left[\frac{\frac{\Omega^4}{\omega^4}(sin\theta)^4}{4\left(1 - \frac{\omega_{pe}^2}{\omega^2} - j\frac{v}{\omega}\right)} + \frac{\Omega^2}{\omega^2}(cos\theta)^2\right]} \tag{8}$$

Here **Ω** is the electron gyro-frequency and θ is the angle between the applied magnetic field and the wave vector. In this case similar to equation (3), ε_r can be divided to real and imaginary part by which attenuation and phase shift are defined. It can be seen that by applying an external magnetic field the permittivity becomes much more complicated but more controllable by the gyro-frequency parameter [15].

3 Experimental measurement techniques for plasma

3.1 Methods of RCS measurement and the radar range equation

The methods of RCS measurement are divided to three techniques [16].

1. Mono-static: When one antenna is used for the transmitter and receiver antenna.

2. Bi-static: When the transmitter and receiver antennas are located on two different platforms.

3. Quasi mono-static: When the transmitter and receiver antennas are separated physically, but located on the same platform.

To measure the RCS of an object, a signal that can be either CW or pulsed CW is sent to the object and then the reflected signal power is measured. A sufficient distance between the antennas and the target is maintained so that plane waves are incident on the target. By using the radar range equation shown in equation (9) we can calculate the cross section (σ) of that object [16].

$$P_r = \frac{P_t G_t G_r \sigma \lambda^2}{(4\pi)^3 R^4} \tag{9}$$

Here P_t, P_r, G_t and G_r are the transmitted and received signal powers, transmitter and receiver antenna gains respectively. R is the range and λ is the incident wave wavelength.

3.2 Experimental results on plasma

As discussed in section (2.1), the methods of RCS measurement are not depended on the plasma or target. Unfortunately, there are not many published articles on experimental RCS measurements of plasma actuators. There are some experiments on measuring RCS from atmospheric pressure air plasma [17] - [20].

In one article the NIG (Negative Ion Generator) and VNA (Vector Network Analyzer) have been used to measure RCS [18]. The RCS is on the order of 10^{-5} to 10^{-4} m^2 over the whole k_α band (26.5 to 40GHz) in room air for a charge density of approximately 1 million/cm^3 at a distance of 40 cm from the NIG needles. These methods are based on coherent Thomson scattering from free electrons and more suitable for remote sensing of nuclear radiation or they use scattering from charged water micro droplets as they may be formed from ion-nucleated water clustering [21], [22]. There is some research on investigating EM wave reflection from a plasma sheet generated in argon for a pressure of around 1.0 Pa. These investigations were performed for two different kinds of electrodes; single hollow and a pair of hollow electrodes for cathode and anode. It is shown that a pair of hollow electrodes can better confine electrons so gives higher electron density. In other words, a pair of hollow electrodes needs less applied voltage and magnetic field for the same electron density. These plasma sheets can be replaced by metal layers for electromagnetic wave reflectors when $n_e \geq n_c = 1.24 \text{ x } 10^{10} f^2$, where f is the incident wave frequency [23] - [25]. Some other authors have worked on scattering measurements from turbulent plasma [26] and for hypervelocity objects to research re-entry electromagnetic phenomenology [27]. For the latter they used a numerical method (FDTD) to show agreement between experimental a numerical results. As can be seen from the above discussion, these kinds of plasma are not suitable for stealth technology and aerodynamic improvement of airframes.

In recent years the effect of DBD actuators on RCS has been noticed [4] along with the aerodynamic improvement techniques [28], [29], so our focus is on DBD generated plasma. An investigation of DBD plasma actuators on RCS was conducted by Wolf and Arjomandi [4]. They did experiments for an array of parallel-plate DBD actuators in an anechoic chamber and they concluded that DBD has no significant effect on RCS. The reasons are the very short lifetime of electrons for atmospheric air plasma and the discontinuous contribution of free electrons by the plasma discharge. This test was done in stationary conditions and atmospheric air plasma for which electron lifetime is very short. In this research the maximum number of parallel asymmetric electrodes is four. Some researchers tried to optimize the plasma generation parameters including discharge current and voltage, PRF (Pulse Repetition Frequency), barrier dielectric and the number of electrodes in an array [28], [29]. It has been shown that by increasing the voltage, the discharge current, energy and electron density all increase, but PRF slightly affects the plasma parameters. The shortening of the rise time increases uniformity of plasma. Also pulse polarity has no effect on electrical parameters. The dielectric or barrier material can affect the electrical parameters. For instance, the discharge current and electron density are higher while using epoxy as the dielectric layer instead of glass or PTFE under similar conditions [29].

Since DBD actuators are used to improve aerodynamic parameters of airframes, it is proved by increasing the number of electrodes in an array, we can improve time-averaged ionic wind velocity up to 8 m/s at 0.5 mm from wall [29]. Non-stationary measurements of induced wind show that DBD actuators can generate a pulsed velocity at the same frequency as the applied voltage [29]. In this research the effect of grounded electrode width, electrode gap and dielectric thickness are investigated and optimized numbers are measured. An important result may be the effect of the applied voltage frequency on the wind velocity. By increasing the frequency, the velocity increases; that can be due to first, increase in applied voltage slope by increasing the frequency and second, the mean transferred charge increases with frequency inducing more collisions between ions and gas. It also shows that by adding each electrode to the array, the velocity increases $1 m/s$ on average. This experiment was conducted with up to four electrodes, but the effect of increasing the number of actuators on the velocity can be the subject of future investigations. One way to improve ionic wind velocity is increasing the applied voltage however, increasing the applied voltage causes bright filaments to occur at the surface of the actuator beyond a critical voltage and subsequently decreases the performance [29], [30].

In terms of power density in plasma an experiment shows when $P < 2\ \mathrm{W/cm^3}$ the plasma is homogeneous and can be modeled by an RLC equivalent circuit, but when $P > 6\ \mathrm{W/cm^3}$, the plasma gets filamentary and the RLC model no longer works. For modeling of this plasma one needs to use parallel resistive model [31].

4 Numerical modeling techniques for plasma RCS

In contrast to published experimental results which lack a comprehensive study, there are many more articles on numerical methods of evaluating RCS in plasma [32] - [34]. The most common method used for simulation of RCS in plasma is FDTD (Finite Difference Time Domain) [32]. The FDM was first developed by A. Thom in 1920s and then FDTD was introduced by Yee in 1966. The main advantages of FDTD are the simplicity of the algorithm and the availability of many commercial simulators. The disadvantage of FDTD is that the error increases for complex geometries [35]. Some articles present FDTD implemented for well-known geometries like cylindrical, spherical or a metallic plate or cone covered by plasma and they have calculated FDTD in one, two and three dimensional space [10], [35] - [37]. Since for numerical methods the region becomes limited to a finite region we need to truncate the space. For FDTD implementation we need to match boundary conditions while the space goes to infinity. A method developed by Berenger called perfectly matched layer (PML) must be used to decrease computation error of this truncation [38]. Also when FDTD is calculated in the near zone, we need to use some near zone to far-zone transformation [39].

Chaudhury and Chaturvedi investigated and optimized RCS reduction using 3-D FDTD [10]. The RCS of a flat plate covered with cold collisional inhomogeneous plasma was studied in this research. Existing “low observable/stealth/RCS reduction (RCSR)” designs of an aircraft tend to make use of special aircraft shapes, or of microwave-absorbing coatings, in order to reduce the RCS. However, there are situations where these techniques may not be effective, such as with the use of a wide range of frequencies in the radar [10].

Collisional un-magnetized plasma, which has a complex dielectric constant, can be used as a good absorber of EM waves over a wide range of frequencies. This absorption leads to a reduction in the RCS over a wide frequency range [7], [10], [11]. Two problems have been considered. In problem 1, using experimentally reported plasma density profiles, they have observed some interesting features in the bi-static RCS and provided simple physical interpretations for some of these features. The simulations confirm that a plasma shroud can successfully be used for reducing the RCS of a flat plate at almost all scattering angles, although the RCS could increase at some other angles. This is a novel extension of the FDTD method for the calculation of the bi-static RCS of an object shielded by non-uniform collisional plasma. Problem 2 involves an optimization study for the input power required to achieve a desired RCS reduction (RCSR), examining a variety of plasma density levels and spatial profiles. For this optimization study, they have considered helium plasma produced by a high-energy electron beam. They find that the maximum achievable reduction increases monotonically with power up to an optimum point, beyond which the RCSR decreases, finally showing some tendency to saturate. This is of practical importance and indicates the usefulness of FDTD simulations in identifying the optimal point. Furthermore, at a given power level, there can be a considerable scatter in the RCSR achievable. This is because various combinations of the plasma parameters, differing considerably in their RCSR abilities, could require the same power to sustain them. Simulations would be of great use in helping to identify the best profiles to be used for a given input power level.

In order to implement FDTD for wave propagation we need to solve Maxwell’s curl equations, yielding spatiotemporal variation of the electric and magnetic fields;

$$\nabla \mathrm{x} \vec{E} = -\mu \frac{\partial \vec{H}}{\partial t} \tag{10}$$

$$\nabla \mathrm{x} \vec{H} = \epsilon \frac{\partial \vec{E}}{\partial t} + \sigma \vec{E} \tag{11}$$

Here, $\vec{E}$ and $\vec{H}$ represent the electric and magnetic field intensities. If the medium is not dispersive, the conventional FDTD method can be used over a wide frequency band, where the constitutive parameters such as σ, μ, and ε are specified as constants. Performing FDTD calculations for frequency-dependent media like plasma over a wideband of frequencies requires a recursive convolution [10]. In the present work, however, the calculations are limited to a single frequency, but for 3 different frequencies; hence, they have used the conventional FDTD method with constitutive parameter values that depend only on the local plasma density. They have used an Epstein profile for electron density and the maximum RCS reduction achieved for backscatter direction ($\theta = 0$) is around 34 dB.

Another method used for RCS simulation in plasma is FEM (Finite Element Method). The advantage of this method is the accuracy and the minimum error for complex geometries [35]. FEM is not widely used for RCS in plasma, but there are some articles of RCS simulation by FEM for jet engine inlet [41] - [42]. This method is similar to FDTD and needs PML [43].

There are some other numerical methods reported in open literature. One method is the method of impedance transformation [44]. The advantage of this method is the simplicity of calculations, but the disadvantage is that this method assumes uniform plasma which cannot be practically generated, so the error is high. This method was modified by dividing the plasma slab to parallel thin slabs and assuming plasma uniformity or a constant permittivity for each slab [15]. By this modification the error level decreases, but the volume of memory needed for calculations increases exponentially by the number of parallel slabs [15]. In some articles analytical methods are used for RCS computation [45]. This method is suited for well-known simple geometries like a cylinder or sphere.

Another method which along with FEM is in the group of variational methods is the method of moments or MOM. In the open literature we found no articles using the MOM for RCS simulation in plasma, but there are some articles for RCS calculation from antenna or aircraft [46], [47]. The main benefit of MOM is simplicity as it is for FDTD. The articles mentioned are for the cases in which the wave equation coefficients are constant but for plasma environments the permittivity is a function of frequency and location so finding a Green's function to satisfy the final integro-differential equation obtained in MOM may be difficult or impossible and it is the main drawback of the MOM method.

5 Conclusions and recommendations for future work

In this emerging field of plasma actuators for aerospace vehicles there is concern that the vehicle RCS may be increased by such actuators. In this study we have examined the open literature to first describe the plasma and its relevant properties to radar, then to examine experimental measurement techniques for radar cross section measurement of plasma, and finally to determine which numerical techniques are used to model the plasma. Plasma at atmospheric pressures has been relatively unexplored compared to reduced pressure plasma so there is greater opportunity for research contributions here. Electron density, collision rate, and electron lifetime are key parameters that will strongly influence the plasma behaviour. The effect of magnetic fields on the plasma opens a new dimension of opportunities along with considerable complexity in modelling. Plasma properties are often measured through reflectometry which is very similar to RCS measurement. Conventional RCS measurements can be used to determine the effects of plasma actuators. The finite-difference time-domain method appears to be the most published method of simulation and this can be either user developed or commercial based tools. In either case the material properties are altered to reflect the plasma properties.

Questions that remain for future work on plasma actuators include determining whether the plasma can be optimized to minimize RCS. In case of plasma thickness is very small it would present limited opportunity to interact with the electromagnetic wave. The presence and effect of an ion plume associated with the plasma is also of interest. Given that at atmospheric pressures the collision rate is very high there will be very little travel of electrons away from the actuator region. Electrons provide the main interaction medium for electromagnetic waves with plasma so that an ion plume may have little impact. However, at high altitudes and high speed the pressure is so much lower and electron lifetime is much longer potentially resulting in a plume of plasma that affects the RCS. In order to determine the effect of the plume on a high speed object's RCS, it will be necessary to know the pressure and effective collision frequency to predict the scattering and attenuation capabilities of the plasma. Finally, the opportunity to utilize magnetic fields to further enhance the plasma should be investigated as these modifications can be as simple as DC magnets.

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List of symbols/abbreviations/acronyms/initialisms

DBD	Dielectric Barrier Discharge
DND	Department of National Defence
DRDC	Defence Research & Development Canada
DRDKIM	Director Research and Development Knowledge and Information Management
ECR	Electron Cyclotron Resonance
FDTD	Finite Difference Time Domain
FEM	Finite Element Method
LTE	Local Thermodynamic Equilibrium
PML	Perfect Matched Layer
RCS	Radar Cross Section
RCSR	Radar Cross Section Reduction
R&D	Research & Development
RF	Radio Frequency

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It has been noticed that plasma with different characteristics could provide distinct response to electromagnetic waves, i.e. could reflect or absorb them. The Flight Mechanics Group at DRDC Valcartier is leading a Technology Investment Fund (TIF 11az) research project aiming to improve understanding on the interactions between plasma and electromagnetic waves.

Plasma actuators are receiving significant research attention in aerodynamic applications. Associated with these plasmas is the potential to change a vehicle's radar cross section (RCS). This study examined the open literature in order to identify the plasma parameters affecting RCS as well as investigating published experimental and numerical modeling methods to evaluate the plasma effect. Recommendations for future work are presented including the use of static magnetic fields to modify the plasma.

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