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Introduction to Radar Cross Section Reduction

1.1 Introduction

The concept of stealth or radar cross section (RCS) reduction and control has been a topic of interest since World War II. Attempts were initially made to reduce the detectability of the aircraft by employing wood and other composites as aircraft materials since they were less reflective to the radar waves than a metal. Following the initial systematisation, one realised that shaping and coating [by radar-absorbing materials (RAMs)] emerged as the primary techniques for the RCS reduction (RCSR).

RCSR through shaping is readily apparent in case of stealth fighter aircraft F-22. The edges at principal and drooping ends of wings and rear end of the aircraft have similar angular sweep. Further, the fuselage and canopy are smooth-surfaced with slopes at sides. The shapes of the surface interfaces, such as the doors at bay and the seam of the canopy, are saw-wave-type. The vertical airfoil of aircraft tails is slant. The front side of its engine is obliterated and includes a serpentine-shaped engine duct. Finally, all the weapons are stored within the aircraft itself. These alterations in the conventional shape of the aircraft resulted in considerable RCSR of the aircraft.

In contrast, RAM coatings have been used since 1950s to achieve low-RCS aircraft design. RAM was also useful in mitigating the coupling effect and cross talk between the antennas mounted on the surface of the aircraft. The reconnaissance airplane Lockheed U-2 and the fighter aircraft F-117 are few examples where RAM has been used for RCSR.

Sufficient knowledge base was created over time regarding the scattering behaviour of aircraft structures. The parameters that played a significant role in overall scattering characteristics of these structures were identified. For example, flat plates and cavities were observed to result in large radar return at normal incidence. Similarly, the inlet and exhaust systems of the fighter aircraft were identified as significant contributors towards the aircraft RCS in front-on and rear-on angles, while its vertical tail dominated the radar signature from other angles at the sides.

Numerical techniques were developed over years for the quantitative estimation of scattering from different parts of the aircraft structure. This facilitated the balanced design of aircraft with optimum RCS. Such aircraft include the F-117A- and B-2-type stealth aircraft.

The frontal RCS can be reduced by avoiding shapes and angles of high radar return. Multiple reflections are one of the important factors apart from orientation of the shape and polarisation of the impinging wave. If the wave enters into a long, closed perfect electric conductor enclosure, it undergoes multiple bounces and may result in large scattered field towards the radar source. The field associated with radar return can be reduced by coating the inner surface of the enclosure with RAM or redesigning the shape of the enclosure. For example, a curved duct can be useful in increasing the reflections significantly, thereby attenuating the incident energy without any adverse effect on its aerodynamic performance. Such a cavity, in particular, should have large cross-sectional aspect ratio. The SR-71 engine duct inlet is an example of such multiple bounce low-RCS design.

A low-frontal RCS is important in aerospace vehicles. However, it is a real challenge to achieve this when a large radar antenna exists within the nose radome. Attempts have been made to reduce the frontal RCS by mounting the radar antenna at an angle offset to the nose, but it does not lead to low observability. Another option is to redesign the slender nose as done in the cases of YF-23 and Boeing X-32 aircraft. The main aim of this is to block the signals from hostile radar sources to enter into the nose cone radome. This can be done by diverting the impinging radar waves or by reflecting them back from a flat plate-like antenna. Alternately, one can adapt the antenna pattern and place nulls towards the hostile radars; this may be considered as an example of *active RCSR*.

The RAMs and alignment of inlet surfaces require intelligent design. Moreover, the frequency range over which low observability is required is large and covers two to three orders of magnitude frequently. It is also known that the constitutive parameters of coatings depend on frequency and temperature. RAMs are discussed further in Section 1.3.2. Within the engine nozzle of the vehicle, air passes with a large velocity thereby rising the temperatures very high. Thus, the RAM coatings are expected to be functional at high temperatures. Russian researchers have developed coatings and techniques in the stealth design that can reduce the head-on RCS of a Sukhoi Su-35 fighter aircraft by a factor of 10, thereby halving the radar range for the target detection. Moreover, the Su-35 aircraft consists of a treated cockpit canopy that reflects the impinging radar waves and conceals the RCS contribution from metallic components.

Such electromagnetic (EM) designs attempt to alter the aircraft surface characteristics with an objective to make the aircraft 'invisible'. Essentially, the effective area of the aircraft reflecting EM waves that are detected by the radar is reduced. This concept is known as stealth.

The stealth techniques initially employed were frequency dependent and, thus, limited in their overall effectiveness. The RCS estimation and control involves many researchers and engineers of various disciplines; the attributes pertaining to EM, signal processing, materials, structural aspects, aerodynamics, etc. have to be considered simultaneously.

1.2 The concept of target signatures

Although EM signatures are the primary concept that come to our mind in the context of the detection of aerospace vehicles, other signatures are also considered for this purpose. These include acoustic (noise), optical (visible), infrared (thermal) and radar signatures.

Acoustic signatures: The acoustic signatures of an aircraft (2 cm–16 m wavelength) are due to the aerodynamic noise from its vortices, wings, rotors, propellers and engines. The intensity of noise is directly proportional to the wingspan loading and speed. Reduction of such signatures contributes towards acoustic stealth. Electric motors are less noisy than turbo and piston engines, but are limited to short-endurance applications. However, small mass and low aerodynamic drag contribute significantly to noise reduction. Keeping the distance constant, the sound attenuation is inversely proportional to the wavelength square. This makes low-frequency noise an important factor for acoustic stealth. This is the reason for mounting turbo engines above the wings in large tactical aircraft, which facilitates shielding of the compressor noise and the efflux noise from the ground.

The type of engines is also an important factor for the generation of acoustic signatures. A four-cycle piston engine has more fuel consumption efficiency than a two-cycle one; the frequency of noise is comparatively lower in the two-cycle piston engine. This leads to lower noise attenuation in four-cycle piston engines and hence make them less preferred from the acoustic stealth point of view.

Such combustion noise can be reduced by coating the engine with sound-absorptive materials. The increase in weight due to extra coatings can be mitigated by covering only those areas that emit.

Optical signatures: The size and shape of a vehicle are important factors for detection by optical signatures. The contrast against the background is also crucial in fixing the threshold of detection. The background luminance depends upon the atmospheric conditions and the target position with respect to the sun. The surface texture of the vehicle and the atmosphere-reflected illumination are other factors that decide the strength of optical signatures (0.4–0.7 μm).

Thermal signatures: The thermal or infrared signatures (0.75 μm–1 mm) are due to the heat generated by the aircraft engine jets, propellers and rotors. The exhaust heat from the aircraft can be prevented by travelling towards the ground. This path diversion enables reducing the detection probability of the aircraft by the detectors at the ground base. Moreover, low-emissive materials (e.g. Ag, Al) can be used to avoid radiation. The engine exhausts should be screened by other airframe components to deflect the thermal radiation away from the ground.

Radar signatures: Radar (3 mm–30 cm wavelength) signatures are related to the *radio frequency* (RF) emissions from the aircraft. These are primarily reflected RF signals. They can be reduced by either applying RAM coatings or shaping the aircraft. Special attention may be given to the hot spots including the edges and corners of the aircraft. Care must also be taken so that no surface of the aircraft is illuminated by radar signal at normal incidence. Likewise, for the signals incident at smaller angles, vertical surfaces such as fins become significant contributors to radar signatures. It is also desirable to avoid corner-reflectors-type geometry, since surfaces meeting at right angles give rise to strong radar returns. The most significant contribution comes from antennas/sensors mounted over the vehicle. These sensors and antennas might add to the RF signatures of the vehicle.

1.3 Radar cross section of an aircraft

RCS is an estimate of observability of a target, which in turn, depends on its external features and EM properties. The RCS essentially relates the EM energy of the receiver reflected from the target to the incident EM energy (Knott et al. 2004). When EM wave is incident on a body, part of the energy is absorbed. The remaining energy is accounted by the phenomena of reflection and diffraction. An important characteristic that explains the EM scattering phenomenon is the *electrical dimension* of the scatterer. The point of concern is that the radar signal returning from shapes other than spherical ones depends on the polarisation of incident wave. The polarisation of EM waves may vary with scattering. Surface ray propagating on a general surface has finite torsion and its path of propagation cannot be restricted to a plane. Thus, its direction changes continuously, that leads to a change in polarisation.

The RCS of an object has an apparent size as seen by the radar. It is essentially a coherent summation of the contributions from various scattering centres of the target once illuminated by the radar. In other words, the target structure including the various hot spots would re-radiate the EM energy impinging on the target. These individually scattered fields with the associated amplitude and phase add up to the resultant scattered field. The total scattered field includes reflection in specular directions, diffraction at sharp edges, corners, multiple scattering, surface waves, creeping waves, shadowing effect, etc. Thus, the shape and size of the target, and hence the scattering centres, decide the extent and scintillation of the RCS with respect to the aspect angle and frequency.

An aircraft, for example, would return the nose-on incidence mainly due to the engine inlets. If one moves away from the nose-on angles, the principal wing edge becomes one of the major contributors to the overall RCS. For the angle of incidence beyond this limit and up to 70°, the scattering is primarily from the forward fuselage and engine nacelles. Beyond this and up to normal incidence, scattering in the broadside direction has significant contribution from the fuselage and vertical stabilizers. Similarly, when the aspect angles are near ±180°, the engine exhausts dominate the scattering. Thus, the overall structural RCS of the aircraft will be coherent summations of all such returns.

Further, the aircraft structure has numerous sensors and antennas mounted over it for various applications. This may enhance the scattering cross section of the aircraft considerably. The scattering from the antenna or antenna array system is due to its structure and feed network. When the feed network is matched, the scattering cross section is termed as antenna structural RCS (Shrestha et al. 2008). This is due to the fact that in such a condition there will be no reflections from the feed and the antenna RCS will be due to its structure only. In other words, the antenna structural RCS is a function of currents induced over the surface of the antenna by an incident wave (Jenn 1995). It must be borne in mind that although other definitions based on varied interpretations are prevalent for antenna structural RCS in an open domain, the definition mentioned above shall be used in this book.

When the feed network is not matched, the antenna RCS will be due to its structure as well as the reflections from the feed network. This is referred to as *antenna mode scattering* (Yuan et al. 2008). Thus, the antenna RCS is the sum of the antenna structural RCS and antenna mode scattering.

The structural RCS of the antenna not only depends on the antenna structure but also on the platform (aircraft) over which it is mounted (Perez et al. 1997). The aircraft may be considered as a set of wedges and facets, or as a hybrid of parametric surfaces (Wang et al. 2001), or even the Non-Uniform Rational B-Spline (Domingo et al. 1995). This is followed by the use of numerical electromagnetics techniques such as uniform theory of diffraction (UTD), physical optics (PO), Electronic Counter Measures (ECM), Method of Moments (MoM), Finite Difference Time Domain (FDTD), etc. for estimating the total scattering to arrive at the total structural RCS of the aircraft. Since the asymptotic high-frequency techniques are often involved, its prerequisite, viz. the ray tracing is discussed in Section 1.3.1.

1.3.1 Ray-tracing techniques

The ray tracing, in principle, determines every possible ray-path between the source and the observation point. The computational cost of ray tracing, being a geometric method, does not depend on electrical dimensions of the structure. The ray-paths are based on generalised Fermat's principle. The direct ray, and all the reflected, double reflected, diffracted, reflected-diffracted, surface wave, and creeping waves are taken into account.

In free space, the principles of *geometrical optics* (GO) are employed. A complex field represents the amplitude and the direction of the wave. Ray tracing is essentially the determination of exact location of the *reflection*, *launching* and *shedding points* on the surface. The field associated with the ray at the receiving point is determined by coherent summation of each individual contribution of these ray-paths.

In RCS estimation, ray tracing is essentially used with high-frequency asymptotic methods when the electrical dimensions are greater than the wavelength of the impinging wave. These asymptotic methods include geometrical optics (GO), geometrical theory of diffraction (GTD), physical optics (PO), physical theory of diffraction (PTD), uniform theory of diffraction (UTD), etc.

In fact, for electrically large objects, low-frequency approaches, *viz.* the ent method, finite element method (FEM) are often infeasible. Despite the availability of high-speed, large memory computers, the size of the object that can be handled *via* such methods is too small for any use in actual cases. In contrast, the high-frequency methods, although simple, provide more accurate results. The simplicity of these methods lies in the assumption that each part of the target scatters energy independent of all the other parts. Therefore, the fields induced on a section of the target are only due to the wave impinging upon it, and not on the scattered waves from the other parts. This makes it relatively simple to estimate the induced fields and to integrate them over the body to obtain the RCS.

A ray at a given surface point may be defined in three possible ways: (a) finite-length (point-to-point) rays, (b) semi-infinite-length (point-to-direction) rays and (c) infinite-length rays. There can be two symmetric sub-configurations, *viz.* for (a) near-field to far-field transformation and (b) far-field to near-field transformation. Such analysis may be handled on the basis of the reversibility of the ray-path. The last configuration, infinite-length rays, may be either monostatic or bistatic.

Most critical step in ray-tracing method is to obtain the intersection of rays with the surface. Several methods have been introduced in the open domain to determine the point of intersection. The planar/non-planar surface at which the ray hits is divided in different ways to determine the point of reflection. One such method involves recursive subdivision within bounded volume (Whitted 1980). Here the surface is divided and the bounded volume is produced for each sub-surface. This process continues till the ray does not intersect the surface. The bounded volume may be considered as a sphere or a closed box (Whitted 1980, Pharr and Humphreys 2010). Another method is to divide the surface into triangular facets (Kaijiya 1982, Snyder and Barr 1987). However, the faceted surfaces lead to high computational cost.

This problem of high computational cost can be circumvented algebraically by converting the parametric surfaces into implicit formulation (Manocha and Demmel 1994). This results in a problem of intersection of two planes in a parametric space. The solution of the system of equations provides the curves formed by the plane–surface intersection. The numerical technique based methods, *viz.* Laguerre's method (Kajiya 1982), recursive Newton method (Martin et al. 2000) may be used for the solution. Alternatively, the implicit equations can be solved by expanding them as a high-order matrix determinant (Manocha and Demmel 1994). However, these methods are limited by their increase in computational complexity for higher degree surface. Some researchers approximate the surfaces as a plane surface and determine the initial point from the ray intersection with bounded volumes (Martin et al. 2000, Sturzlinger 1998). Optimisation algorithms like quasi-Newton iteration and conjugate gradient method can also be used for estimating the point of intersection (Joy and Murthy 1986).

If there is no intersection, the ray will travel towards the receiver. This is referred to as the direct ray. The field associated with the direct ray at a distance s is expressed as (Pathak and Kouyoumjian 1974, Pathak et al. 2013)

$$E_{Direct}(s) = E_i(0).A(s).e^{-jks}, \tag{1.1}$$

where e^{-jks} is the phase of the ray-field and $k = \frac{2\pi}{\lambda}$.

$A(s)$ is the amplitude variation given by

$$A(s) = \sqrt{\frac{\rho_1 \rho_2}{(\rho_1 + s)(\rho_2 + s)}}, \tag{1.2}$$

where ρ_1 and ρ_2 represent the principal radii of curvature of the wave front at a given surface point.

When a ray hits the surface, its propagation depends on the surface characteristics. For a transparent or semi-transparent surface, the rays may get reflected from the surface or transmitted through it. The attenuation in the ray-field depends on the constitutive parameters of the surface. The transmitted field at the distance *s* is given by

$$E_T(s) = E_i \,.\, A^t \,.\, T \, e^{-jks}, \tag{1.3}$$

where the transmission coefficient depends on the polarisation of the incident ray (Jordan and Balmain 1976). The amplitude variation A^t depends on the radii of curvature of the surface and that of the incident wave, given by (Kouyoumjian 1965)

$$\frac{1}{\rho_1^t} = \frac{1}{2}\left(\frac{1}{\rho_1^i} + \frac{1}{\rho_2^i}\right) + \frac{1}{f_1}; \quad \frac{1}{\rho_2^t} = \frac{1}{2}\left(\frac{1}{\rho_1^i} + \frac{1}{\rho_2^i}\right) + \frac{1}{f_2}, \tag{1.4}$$

(f_1, f_2) being the focal distances and (ρ_1, ρ_2) being negative (positive) for the concave (convex) surface.

The reflected field on the surface is given by

$$E_R(s) = E_i \,.\, A^r \,.\, R \,.\, e^{-jks}, \tag{1.5}$$

where the reflection coefficient, *R,* depends on the nature of polarisation (parallel and perpendicular).

Another phenomenon that takes place when a ray hits a corner or an edge is diffraction. Rays that hit normal to the surface generates the waves of cylindrical wavefront. In contrast, for obliquely incident rays, diffracted wave will be conical. The diffracted field on the surface is given by (Kouyoumjian 1965)

$$E_D(s) = E_i \,.\, A^d \,.\, D \,.\, e^{-jks}, \tag{1.6}$$

where *D* is the diffraction coefficient that depends on polarisation.

When a ray hits the surface tangentially, it travels along the local geodesic of the surface and leaves the surface tangentially. This is referred to as the *creeping wave*. These ray trajectories are determined using the generalised Fermat's principle. Further, a ray may undergo multiple interactions, e.g. reflection followed by an edge diffraction and then again by transmission. The drawback of ray tracing is that the computational complexity increases due to such multiple propagation phenomena. Therefore, acceleration and optimisation procedures are required towards efficient and fast solutions.

1.4 RCS reduction

Presently, the extensive knowledge base of passive techniques can be employed for controlling the EM scattering. These passive techniques frequently involve either shaping or applying RAM. The effectiveness of such methods depends on the frequency, incident angle and polarisation of the impinging wave.

The main objective behind shaping the structure is to minimize the amount of energy that is backscattered towards the radar. This type of RCS control has been found to be effective for the monostatic radars. If, for an aerospace vehicle, e.g. aircraft, missile or UAV, the profile of the structure is designed so that only a small angular range is available to the radar, then stealth may be achieved by considering that angular region. However, it is important to keep in mind that RCSR in one aspect angle is frequently accompanied by an increase in the RCS at another aspect angle. Both the approaches of shaping and RAM are often considered simultaneously to achieve the acceptable low observability over the operational frequency band.

Apart from the above-mentioned passive techniques, other methods such as usage of artificial magnetic conductors (AMC) (Paquay et al. 2007), frequency selective surfaces (FSS) and active RCSR have also been proposed towards RCSR. The AMC structure (Yeo and Kim 2009) scatters the incident energy towards offset directions thereby reducing the specular reflection considerably.

The basic difference between the passive and active techniques of RCSR is that in passive techniques, the scattered wave from one part of the target cancels the same from the other part due to amplitude and phase difference while the active techniques involve the cancellation of the incoming wave through destructive interference with the scattered field within the array or sensor-based system. The active cancellation of the impinging waves makes the platform 'invisible' to the probing radar sources.

1.4.1 RCS reduction by shaping

RCSR through shaping is a high-frequency technique based on geometric optics. If the object is electrically large, the incident wave will be reflected mainly towards the specular direction. A cylindrical surface, for example, would produce specular reflections along its length when observed sidewise. A spherical surface would reflect from any point independent of its orientation. Reflections from other directions become significant only when the specular reflections are suppressed or eliminated. The structure is shaped to reduce the edges, surface discontinuities and corners (e.g. dihedrals, trihedrals). The main intention is to redirect the reflected waves in non-specular directions, thereby minimising the backscattering (Lynch 2004).

The shaping must comply with the aerodynamic requirements of the vehicle (e.g. aircraft, missiles, ships, etc.). If the nose of the missile could be made round instead of pointed, the specular reflections would be reduced considerably. Another example is the engine inlets. If the shape of the intake duct is made curved, then reflections from the inside walls of the inlet and the engine can be reduced. Furthermore, the recessing of inlets inside the fuselage would hide the engine opening from the radar. The stealth aircraft F-117 has shaped wings and fuselage designed for minimum reflection towards the radar. The RAS design is based on the principle of reflection. If the angle of incidence is varied from end-fire to the broadside, there is an increase in reflection towards the source.

The backscattered fields due to the edge-diffracted waves are also important contributors towards overall RCS. These diffracted waves are coherent for straight discontinuity and perpendicular incidence (Ufimtsev 1996). Such diffraction takes place at trailing edges of wings of an aircraft, gap between wing and flaps or rudders, edges of cargo doors, etc. Such backscattering can be reduced by either indenting the edges, replacing the surface with electromagnetically soft surface or applying RAM over the surface.

1.4.2 RCS reduction by RAM

Essentially, RAM absorbs the incident EM energy and converts it into heat, thereby reducing the scattered energy towards the radar. RAM is known to be quite effective in controlling the backscattering than forward scattering (Hiatt et al. 1960). RAMs have relatively high values of imaginary part of permittivity and permeability. Such coatings result in change in polarisation of the scattered waves.

Narrowband RAM coatings, such as the Salisbury screen and Dallenbach layer, have been used since 1950s. However, modern radar systems span a wide range of frequency. Hence, the need for wideband RAMs is apparent. A typical RAM employed on aircraft could be a ferrite-based paint or a composite. However, there are significant implications of using RAM. Firstly, most of them are toxic. Secondly, RAM coatings require precise application techniques, as the coating thickness and smoothness must be uniform across the platform.

Ideally a RAM should not impose weight penalty due to speed and pay load considerations. It should possess high mechanical strength and should be anticorrosive, chemically stable and should not get charged at high temperature. It must have a wideband RCSR. Lastly, it should be effective in all directions (Vinoy and Jha 1996). The RAM application process typically involves robotic sprayers that can accurately control the coating thickness. Furthermore, these coatings require strict constitutive parameter tolerances as well as uniformity in order to achieve the desired result. Therefore, the cost of implementation of RAM is often too high. Another issue is that RAM also increases the weight of the platform. This may have notable impact on the vehicle performance aerodynamically.

For different platforms, RAM coatings have been developed with appropriate combination of rubber, cotton-glass, epoxy and mica. Other possibilities are graphite fibres, Kevlar and ferrites. The materials can be of different forms such as sheets, honeycombs, laminates, etc. Ferrite materials in forms of flakes, wires or microspheres can be loaded into glass–epoxy or silicon rubber. The inks and coatings can be applied on kapton film or epoxy honeycombs.

Radar-absorbing paints are also coated over the surface of the vehicles. These paints consist of small ferrite particles that are polarised towards the impinging wave. Such paints are prepared by mixing solid iron oxides with various polymer resins, such as epoxy and plastics. The constitutive parameters including thickness of the paint, fix the resonance frequency for maximum absorption.

1.4.3 Active RCS reduction

For an aerospace vehicle, it is not only the structure of the vehicle that contributes to the radar signatures, but the antennas and sensors mounted on the vehicle are also of concern. Even if the structures are designed efficiently for stealth via shaping and RAM coating, there is a significant contribution from these sensors. The antenna RCS, which has two components, *viz.* the structural mode RCS and antenna mode RCS, is another important issue to be dealt with.

There can be situations when the RCS of the antenna mounted on the platform dominates the RCS of the platform. In such a case, the radiation pattern of the phased antenna array, for example, can be controlled through adaptive weight estimation. This feature relates to active RCS control and, hence, RCSR.

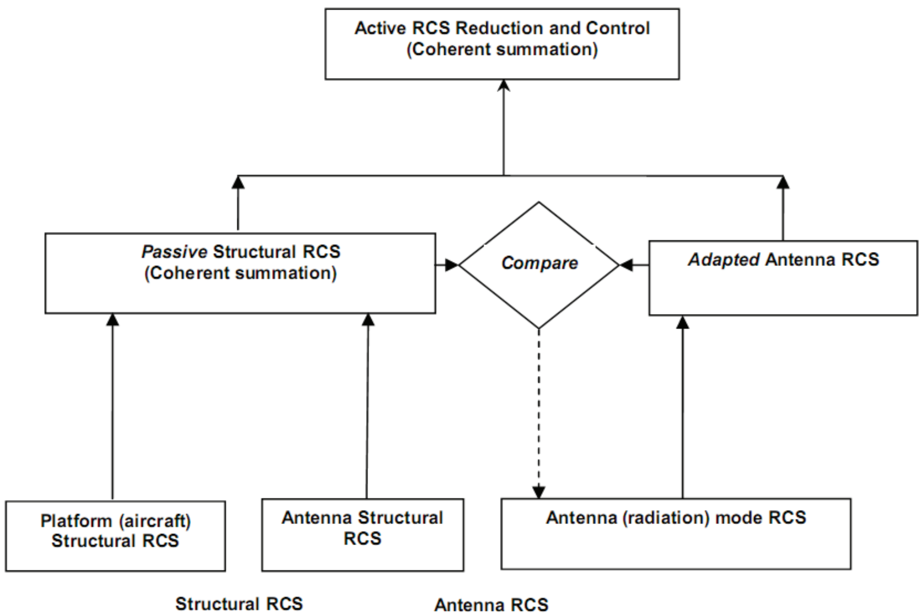

Figure 1.1 The concept of active RCS reduction and control

The active RCSR of a vehicle relates to the adaptive array, digital beam forming and field programmable gate array (FPGA) based system. The phased array along with an efficient weight adaptation generates the pattern nullifying each probing radar and simultaneously maintaining sufficient gain in the desired directions. The FPGA system does signal analysis, database search, and waveform generation and control. The structural RCS and the antenna RCS of the vehicle are determined before hand and stored in database, which is integrated with the active RCS so as to eventually generate low RCS for the aircraft. This is done within the signal processing and control module of the phased-array system. The module analyzes the measured radar signal parameters and thereafter searches the corresponding target echo data in the RCS database, and accordingly makes a real-time adjustment of the coherent echo amplitude and phase parameters.

The active RCSR is essentially a combination of both software and hardware realisation, enabled by utilizing high-speed microelectronic devices, phased-array antenna techniques and signal processing methods. The active RCSR through phased arrays, once coherently integrated, can cancel out the structural RCS of the platform over which the array is mounted, and hence contributes towards a low-observable platform.

The concept of overall active RCSR of an aerospace vehicle is shown in Figure 1.1. The idea is to achieve significant RCSR and a control for arbitrary practical scenarios. It is apparent that the RCS estimation and control of phased arrays is an important milestone towards the overall RCSR of the platform. This involves estimation of the antenna array RCS as well as the