5 RCS Management of Edge Diffracted Waves

5.1 Introduction

Radar absorbing materials (RAM's) applied as a coating on the surface of an object, partially transform the energy of an incident radar beam into heat and reduce the scattered field in some directions. Ordinary RAM's (electric, magnetic or hybrid) can be graded or have multiple layers in order to increase the frequency band. Moreover, they are nearly always homogeneous in directions parallel to the reflecting plate.

However, ordinary RAM's are not effective in absorbing grazing incident waves ($\theta_i \cong 90°$) and are therefore not successful in reducing forward scattering [1]. This fundamental limitation results from the fact that any ordinary RAM, independently of the incident wave polarization, has a reflection coefficient that tends to unity when $\theta_i \to 90°$. This can be inferred from the reflection coefficient expressions (3.43) and (3.44).

For parallel polarized incident waves

$$\lim_{\theta_{2i}\to 90°} R_{//} = \lim_{\theta_{2i}\to 90°} \Gamma_{i//} = \lim_{\theta_{2i}\to 90°} \frac{Z_{c2//} - Z_{s\ell//}}{Z_{c2//} + Z_{s\ell//}} = \lim_{\theta_{2i}\to 90°} \frac{\eta_2 \cos(\theta_{2i}) - Z_{s\ell//}}{\eta_2 \cos(\theta_{2i}) + Z_{s\ell//}} = -1. \tag{1}$$

Likewise, for perpendicular polarized incident waves

$$\lim_{\theta_{2i}\to 90°} R_{\perp} = \lim_{\theta_{2i}\to 90°} \Gamma_{v\perp} = \lim_{\theta_{2i}\to 90°} \frac{Y_{c2\perp} - Y_{st\perp}}{Y_{c2\perp} + Y_{st\perp}} = \lim_{\theta_{2i}\to 90°} \frac{\dfrac{\cos(\theta_{2i})}{\eta_2} - Y_{st\perp}}{\dfrac{\cos(\theta_{2i})}{\eta_2} + Y_{st\perp}} = -1. \tag{2}$$

Ordinary radar absorbing materials are therefore not very useful in reducing the forward scattering of an object.

5.2 Converting the Incident Space Wave into Attenuated Surface Waves

It is conceivable that absorption of grazing incident waves could be realized if some special discontinuity (e.g. an edge, a wire or a grating) were placed along an absorbing layer. Such a discontinuity could partially transform the incident wave into surface wave modes which would propagate and attenuate further along the layer [1]. (See Fig. 5.1.) In fact, gratings are successfully employed in integrated optics as feeding structures for dielectric waveguides where they yield space wave to surface wave power conversion efficiencies of up to 80% [2].

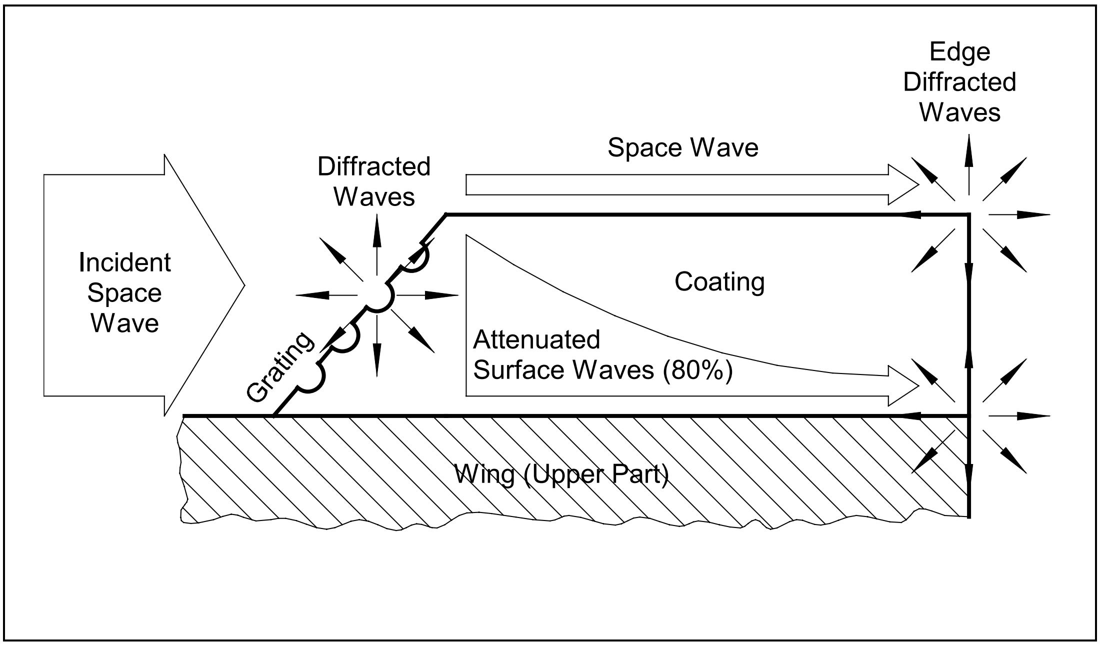

Figure 5.1: Conversion of the incident space wave into attenuated surface wave modes

However, the idea of converting the incident space wave into attenuated surface wave modes has three essential defects for RCS reduction. Firstly, any additional discontinuity creates an additional scattered field. Secondly, the transformation of the incident field into surface wave modes is only partial. Part of the incident field will remain propagating as a space wave to finally interact with the object and reflect. Thirdly, it is extremely difficult, if not impossible, to build an absorbing layer which would allow the propagation of both E-type plane surface waves and H-type plane surface waves. As has been shown in Chapter 3, the longitudinal surface impedance must be inductive to support E-type surface wave modes whereas a capacitive transversal surface impedance is required to support H-type surface wave modes. Thus, the surface impedance needs to be anisotropic to allow propagation of both types of surface waves.

Successfully admitting and then absorbing surface waves in a surface wave absorbing material would therefore require the following actions:

1) Convert as much of the incident space wave field into surface wave modes while trying to avoid generating additional forward scattering. This has to be achieved not only for an incident angle of 90° but also for angles close to 90°. Note also that the incident space wave can have any polarization, which complicates matters even more.
2) Use a coating with an anisotropic surface impedance to enable the propagation of both surface wave types.
3) Moreover, the coating has to have significant losses so that the surface waves are sufficiently attenuated before they hit that part of the structure that causes most of the forward diffracted fields. In the case of an aircraft wing, the problem area which generates most of the edge diffracted waves, is most often either the trailing edge of the wing or the air gap between the flaps or ailerons (See Fig. 1.5 and 1.6). The effect of edge diffraction is at its highest level for edges perpendicular to the radar direction [1]. Step 3 involves maximizing the attenuation constant $\alpha_x = -\mathrm{Im}(\beta_x)$ for all propagating surface wave modes.

Although surface wave absorbers based on the above principles are already commercially available, their successful application under all circumstances has not been reported in literature yet. It is also unclear, if not doubtful, whether these surface wave absorbers are able to support both types of surface waves. As has been pointed out already, the main difficulty of the whole strategy is with the implementation of Step 1 and 2. An edge wave RCS management strategy that does not suffer from these defects will be presented next.

Ordinary surface wave absorbing materials may however still find some useful applications. These are discussed at the beginning of Chapter 6.

5.3 Soft Surfaces

5.3.1 Introduction

The main design goal for the surface wave absorbers discussed in the previous section is to maximize the attenuation constant $\alpha_x = -\text{Im}(\beta_x)$ for all propagating surface wave modes. The strategy presented in this section uses a completely different approach. The intention is to reradiate the incident radar energy in directions away from the radar, rather than to dissipate it.

An important observation is the fact that edge diffraction not only generates surface waves but also space waves. The incident wave can have any polarization depending on the polarization of the radar and the orientation of the target. Therefore, the polarization of the edge diffracted space waves and surface waves is generally unknown.

The effect of edge diffraction is completely absent if no fields are present in the immediate vicinity of an object's surface. First will be examined what is needed to obtain this situation with surface waves. The discussion will be restricted to the case of a coated PEC. However, the same reasoning can be applied to multi-layered structures.

For surface waves to have no field protruding from the coating, it is necessary that $js_{z2} \to +\infty$. In this case, the Hertz function of both the E-type and the H-type surface waves (3.7) and (3.18) will be zero at the interface (z = h). Hence, all surface wave field vectors will vanish at the interface. $js_{z2} \to +\infty$, puts the following requirements on the values of the longitudinal (3.14) and the transversal (3.25) surface wave impedance

$$|Z_{s\ell}| = \left| -\frac{js_{z2}}{\sigma_2 + j\omega\varepsilon_2} \right| \to +\infty \text{ and} \tag{3}$$

$$|Z_{st}| = \left| -\frac{j\omega\mu_2}{js_{z2}} \right| \to 0 . \tag{4}$$

These requirements are met by an electromagnetic soft surface, as is explained in the next section.

5.3.2 Definitions

The most general definition for *an electromagnetic soft surface* is a surface along which the power density flux (i.e. the Poynting vector) is zero for any polarization. This means that no electromagnetic wave of any kind (including space waves and surface waves) will propagate along a soft surface. *An electromagnetic hard surface* is a surface along which only a TEM wave (i.e. space wave) can propagate. The density of power flow usually has a maximum at the hard surface. The names soft and hard surface were chosen on the analogy of acoustic soft and hard surface [3].

Although the terms longitudinal surface impedance and transversal surface impedance were used at a number of occasions in this text, they were not defined in their most general sense yet. In order to do so, it is first necessary to define the directions longitudinal, transversal and normal with respect to the propagation direction of a surface wave. *The longitudinal direction of a surface wave*, $\vec{\ell}$, corresponds to the propagation direction of the surface wave and is tangential to surface of the guiding structure. *The transversal direction*, $\vec{t}$, is orthogonal to $\vec{\ell}$ and also tangential to the surface. Finally, *the normal direction*, $\vec{n}$, is such that $\vec{n} = \vec{\ell} \times \vec{t}$.

The longitudinal and transversal surface impedances are given by

$Z_{s\ell} = -\frac{E_\ell}{H_t}$ and (5)

$Z_{st} = \frac{E_t}{H_\ell}$, respectively, (6)

where E_ℓ and E_t are respectively the longitudinal and transversal components of the E-field at the surface, H_ℓ and H_t are the corresponding components of the H-field.

Soft and hard surfaces can be uniquely defined in terms of their longitudinal and transversal surface impedance.

For a soft surface, the Poynting vector needs to be zero a the surface. This is obtained only if both E_t and H_t are zero at the surface, which, in view of (5) and (6), corresponds to: $Z_{s\ell} = \infty$ and $Z_{st} = 0$. (7)
This requirement is identical with (3) and (4).

Only a TEM wave can propagate along a hard surface. Hence, E_ℓ and H_ℓ need to be zero at the surface. This is the same as requiring:
$Z_{s\ell} = 0$ and $Z_{st} = \infty$. (8)

Soft and surfaces are sometimes wrongfully defined in terms of grazing reflection coefficients. For example, soft surfaces are said to be a surface for which $R_{//} = R_\perp = -1$. However, in the introduction to this chapter was shown that for any material $R_{//} = R_\perp = -1$ at grazing angles of incidence (1) and (2). This would lead to the wrong conclusion that all surfaces are soft surfaces, which can not be true of course.

5.4 The Practical Realization of a Soft Surface

5.4.1 Narrow-Band Soft and Hard Surfaces

The classical way to realize a soft surface is to corrugate an ideal conductor with transverse rectangular grooves (Fig. 5.2) [3]. These act as shorted parallel plate waveguides for the longitudinal polarization and transform the short to $Z = \infty$ at the aperture of the corrugations if the slot depth

$$d = \left(\frac{1+2n}{4}\right)\lambda_n \tag{9}$$

where n is positive integer and λ_n the wavelength inside a groove.
Hence, the transversal component H_t will vanish at the aperture of the corrugations. The transversal component E_t is zero at the top face of the perfect electrically conducting walls. At least three corrugations per wavelength are required for the surface to appear as a soft surface [3].

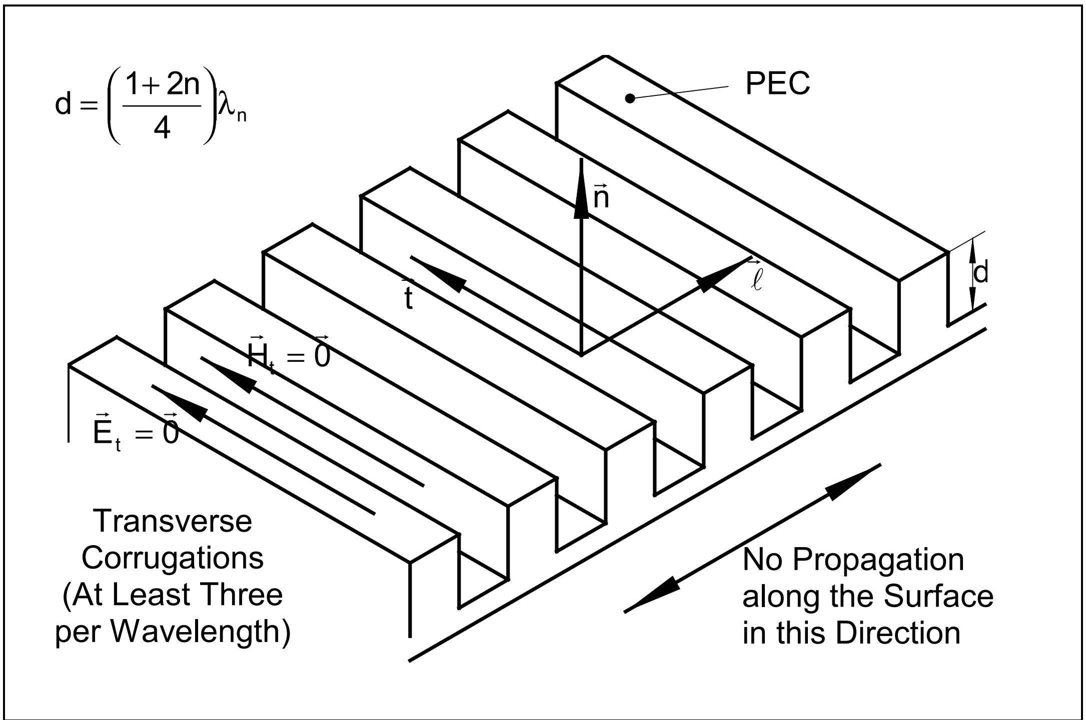

Figure 5.2: A narrow-band soft surface

A narrow band hard surface is obtained by turning the corrugated surface of Figure 5.2 ninety degrees (see Fig. 5.3).

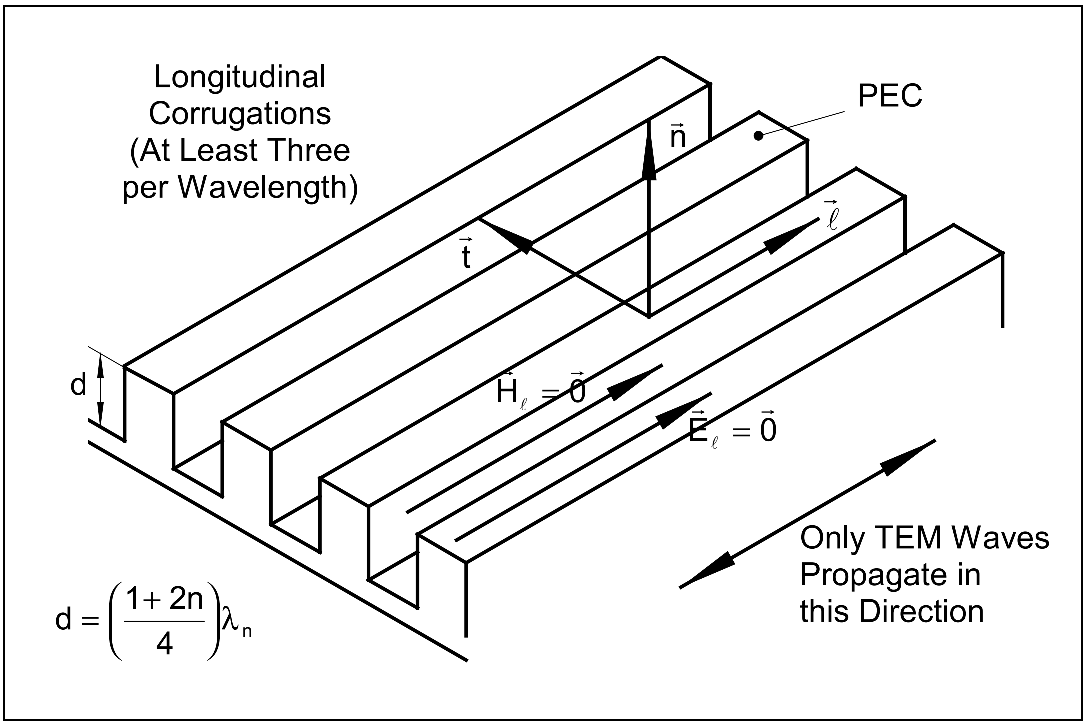

Figure 5.3: A narrow-band hard surface

The grooves of a corrugated surface can be filled with a dielectric in order to maintain the aerodynamic properties of an object. However, corrugated surfaces are still impractical in two ways: they are heavy and they are difficult to manufacture. A much lighter and cheaper alternative is the strip-loaded coating of Figure 5.4 [4].

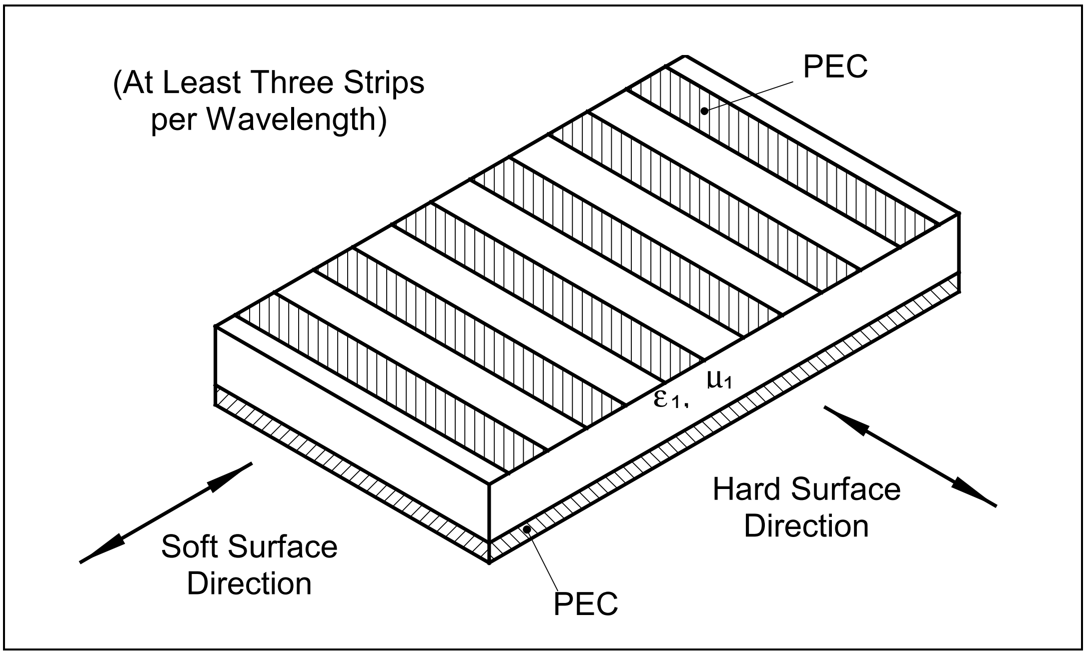

Figure 5.4: A strip-loaded grounded dielectric and/or magnetic slab

5.4.2 A Tuneable Soft Surface

A transversely corrugated surface acts as a soft surface on a discrete set of frequencies only, given by (9). Although dual depth corrugations [4], [5] could double the number of useful frequencies, corrugated surfaces remain impractical because, in general, the operating frequency of a threatening radar is not known in advance. Also the increase in useful bandwidth offered by alternative corrugation techniques [4], [5] is too small to be useful in RCS management.

What is really needed is either a tuneable soft surface, or even better, a broad-band soft surface. A tuneable soft surface could be constructed by replacing the strip-loaded slab of Figure 5.4 with either a strip-loaded electrooptic material or a strip-loaded magnetically biased ferrite slab.

A number of electrooptic materials have the interesting property that their permittivity is light dependent.

The incremental permeability of a ferrite (Fig. 5.5) can be changed by varying the magnetic bias. An electromagnet is used to generate the variable magnetic bias field. A tuneable microstrip antenna on this principle has been reported in literature [6]. However, the relatively high weight of ferrite materials and the energy consumption of an electromagnet make the use of ferrites less favourable than employing electrooptic materials.

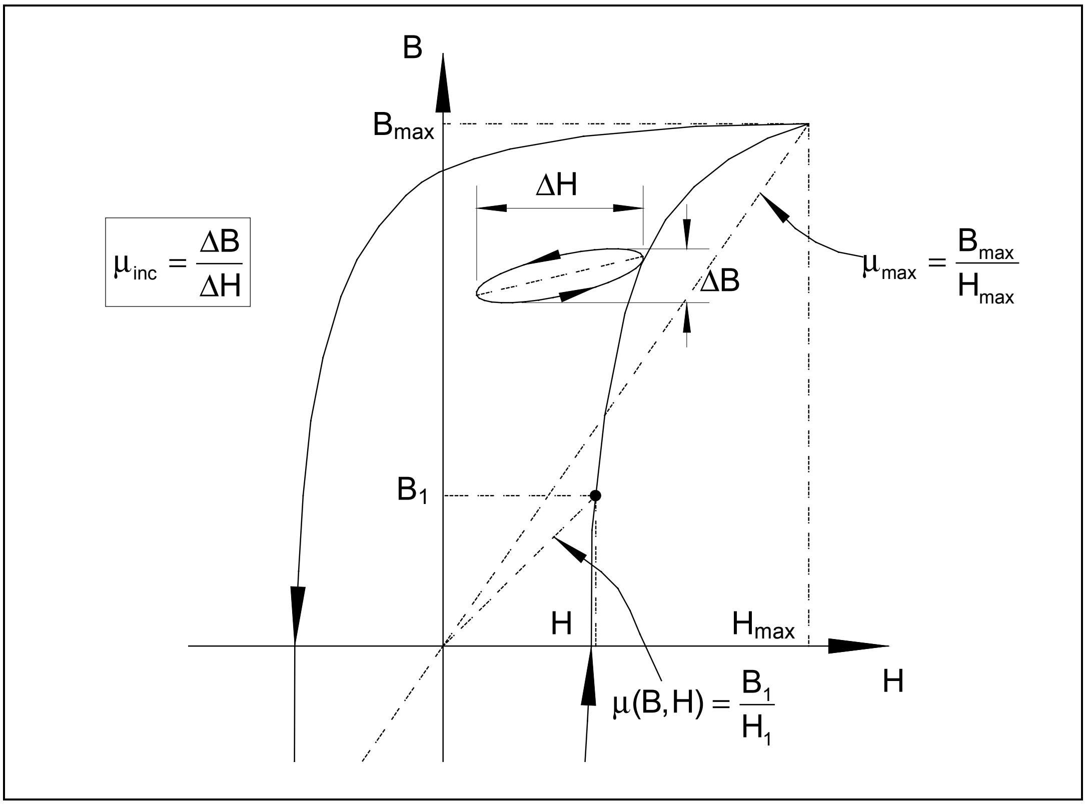

Figure 5.5: Minor hysteresis loop illustrating incremental permeability

5.4.3 What is Needed for a Broad-Band Soft Surface?

A broad-band soft surface would consist of alternate series of good electrically conducting transverse strips and good magnetically conducting strips (see also Fig. 5.4). The tangential components of the electric field vanish at the surface of a *perfect electric conductor (PEC)*. Likewise, the tangential components of the magnetic field are zero at the surface of a *perfect magnetic conductor (PMC)*. A lot of materials are known to be good electric conductors. They are characterized by their high number of free electrically charged particles. On the other hand, magnetic conductors do not exist due to the absence of magnetic charges in nature. However, this is the story for DC. For AC (and hence microwaves) materials that act as good magnetic conductors should, in principle, exist. At least, this is what must be concluded from comparing the definition of complex permittivity with the definition of complex permeability (see also Section 2.2).

Permittivity $\varepsilon = \varepsilon' - j\varepsilon'' - j\dfrac{\sigma}{\omega}$ (10)

where $-j\varepsilon''$ is the loss contribution due to molecular relaxation

and $-j\dfrac{\sigma}{\omega}$ is the conduction loss contribution.

As was already mentioned in Section 2.2, the distinction between the two loss contributions is rather artificial since it is based on the way these loss contributions are measured.
For a PEC: $\sigma = \infty \;\Rightarrow\; \mathrm{Im}(\varepsilon) = -\infty$. (11)

Permeability μ has only one loss contribution due to hysteresis: $\mu = \mu' - j\mu''$. (12)

By analogy to (11), a perfect magnetic conductor (PMC) is characterized by $\mathrm{Im}(\mu) = -\infty$. (13)

Thus, the magnet equivalent of an electric conductor is, for AC, a material with extremely high magnetic losses. It can be shown that the area enclosed by a hysteresis loop (Fig. 5.5) is a measure for the amount of magnetic loss. Most magnetic materials used at microwave frequencies are so called *soft magnetic materials* with thin hysteresis loops (e.g. ferrites) and hence low losses. However, the exact opposite properties are required for a magnetic conductor at microwave frequencies, namely a wide hysteresis loop and hence high magnetic losses. Magnetic materials with such properties are called *hard magnetic materials*. Permanent magnets are always made of a hard magnetic material. However, the use of hard magnetic materials at microwave frequencies has, to the author's knowledge, not yet been reported in literature.

To summarize, replacing the slab in Figure 5.4 with an extremely lossy magnetic material would, in theory, result in a broad-band soft surface. An experimental proof for this hypothesis is not available, but highly desirable.

5.4.4 Applying Soft Surfaces to an Aircraft Wing

Figure 5.6 shows how an ordinary aircraft wing can be retrofitted for reduced RCS. Specular reflections from the leading wing edge are significantly reduced by applying ordinary RAM. Soft surfaces on both sides of the wing suppresses all edge diffracted waves in the radar direction, independently of the radar polarization. Note however that the wing's RCS will increase for aspects other than head-on. (A soft surface is for example a perfect reflector when viewed from above.) Serrations in the soft surfaces are needed as a gradual impedance match for the incoming radar waves.

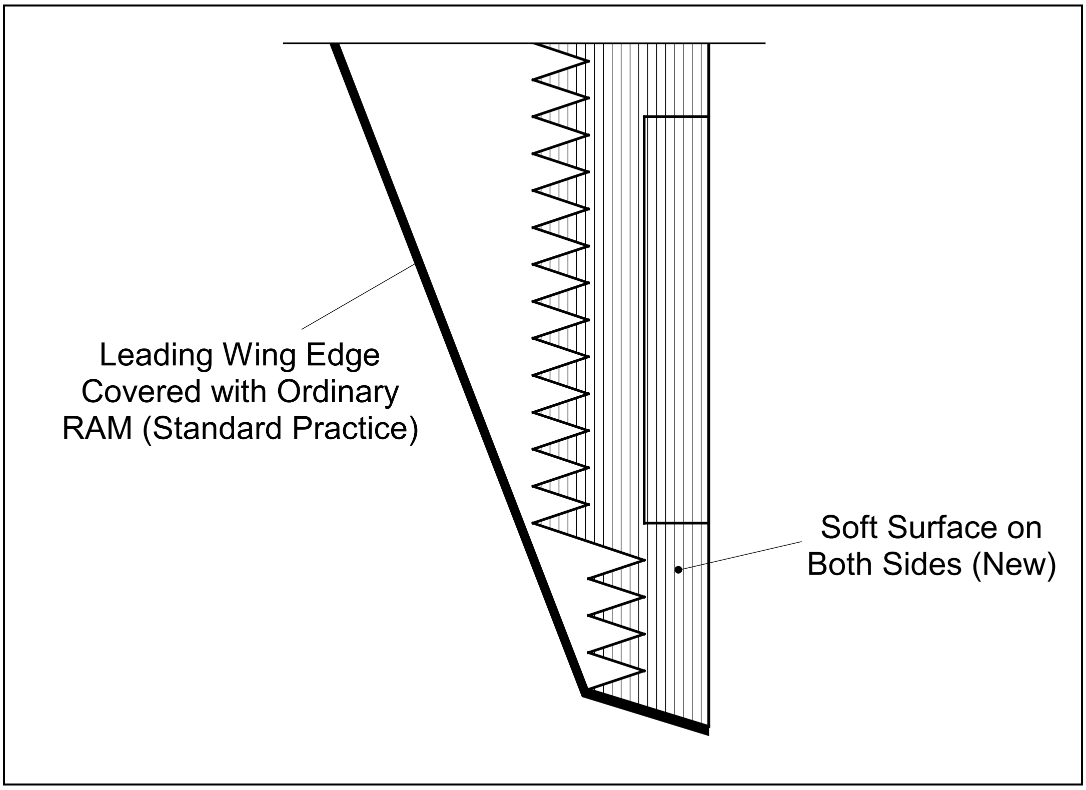

Figure 5.6: Retrofitting an ordinary aircraft wing for reduced RCS

5.4.5 Theoretical Models and Experimental Results Reported in Literature

The corrugated and strip-loaded surfaces are periodic structures. The analysis of periodic structures by means of Floquet's theorem is explained in [7] and [8].

Although no experiments on soft surfaces were conducted by the author, plenty of experimental results are available in literature. In references [5] and [9] a radial surface wave antenna (Fig. 6.2) was employed to measure the efficacy of soft surfaces in suppressing radiation along the surface. A reduction of up to 13dB was measured in comparison with a smooth conducting surface. Numerical simulations using the method of moments gave similar results.

Diffraction coefficients for soft surfaces applied to wedges can be found in [9] and [10].

5.5 Conclusions

Surface wave absorbing materials are not very useful in applications where the radar beam polarization is unknown and/or where the edge diffracted waves come in more than one polarization.

When properly oriented, a soft surface will suppress all radiation (both space wave and surface wave) in the direction of the radar, independently of the radar polarization and the polarization of the edge diffracted waves. In this process, the incident radar energy is not absorbed but reradiated in directions away from the radar.

A narrow-band soft surface can be obtained by corrugating a PEC with transverse grooves of proper slot depth. A much lighter and cheaper alternative is a strip-loaded coating.

Tuneable soft surfaces could be realized by employing electrooptic materials or magnetically biased ferrites.

A broad-band soft surface could in principle be obtained by loading an extremely lossy magnetic material with electrically conducting strips.

Serrations in a soft surface are needed as a gradual impedance match for the incoming radar waves.

5.6 References

[1] P. Y. Ufimtsev, “Comments on diffraction principles and limitations of RCS reduction techniques,” *Proceedings of the IEEE*, Vol. 84, No. 12, December 1996, pp. 1828-1851

[2] P. Lorrain, D. R. Corson and F. Lorrain, *Electromagnetic Fields and Waves Including Electric Circuits*, W. H. Freeman and Co., 3rd Ed.,1988, p. 654 in German Ed.

[3] P.-S. Kildal, “Definition of artificially soft and hard surfaces for electromagnetic waves,” *Electronic Letters*, Vol. 24, No. 3, February 1988, pp. 168-170

[4] P.-S. Kildal, *Research 1993-1995 at Antenna Group*, Department of Microwave Technology, Chalmers University of Technology, Gothenburg, Sweden, p. 15

[5] Z. Ying, P.-S. Kildal and A. A. Kishk, “Study of different realizations and calculation models for soft surfaces by using a vertical monopole on a soft disk as a test bed,” *IEEE Transactions on Antennas and Propagation*, Vol. 44, No. 11, November 1996, pp. 1474-1481

[6] R. K. Mishra, S. S. Pattnaik and N. Das, “Tuning of microstrip antenna on ferrite substrate,” *IEEE Transactions on Antennas and Propagation*, Vol. 40, No. 2, February 1993, pp. 230-233

[7] A. Hessel, “General characteristics of traveling wave antennas,” Chapter 19 in R. E. Collin, F. J. Zucker, *Antenna Theory*, Part 2, McGraw-Hill, 1969

[8] R. E. Collin, *Field Theory of Guided Waves*, IEEE Press, 2nd Ed., 1991, Chapter 9

[9] S. Marci, R. Tiberio and A. Toccafondi, “Diffraction coefficients at edges in artificially soft and hard surfaces,” *Electronic Letters*, Vol. 30, No. 3, November 1993, pp. 203-205

[10] M. Albani, F. Capolino, S. Maci and R. Tiberio, “Diffraction at a thick screen including corrugations on the top face,” *IEEE Transactions on Antennas and Propagation*, Vol. 45, No. 2, February 1997, pp. 277-283