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A combined electromagnetic and acoustic analysis of a triaxial carbon fiber weave for reflector antenna applications

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ABSTRACT

Fiber composites are widely used for space applications such as antennas, solar panels and spacecraft support structures. This paper presents a combined electromagnetic and acoustic analysis of a triaxial carbon fiber weave structure, designed for ultra lightweight reflector antennas in satellite communication systems. The electromagnetic and acoustic performance of the structure are analyzed over a wide range of parametric studies, both at a microscopic and mesoscopic length scale. The electromagnetic study indicates that the main parameter governing the electromagnetic reflection performance of the weave is the electric conductivity of the carbon fibers, given that the weave structure is significantly smaller than the wavelength of the incident signals. The acoustic study identifies a critical threshold in the mesoscale geometry in order to avoid a critically high resistive behavior of the weave structure, driven by viscous effects. Design guidelines are drawn from these analyses in order to achieve a trade-off between the electromagnetic reflection properties and the resistance to acoustic loading of such composite materials. These combined analyses allow to deepen the understanding from both an electromagnetic and acoustic perspective in order to open for some new design possibilities.

1. Introduction

For many years, reflector antennas have been widely used in satellite communication applications. The conditions in space are very harsh with significant temperature effects and thermal cycling, radiation and vacuum, at the same time satellite reparations are very hard to perform. This implies that designing a space antenna is a very delicate matter where aspects such as the weight and size of the antenna are very important to take into consideration [1, Ch. 4]. The current satellite communication situation consists of high demands of increasing communication data rates between satellites and ground stations. To this end, large aperture reflector antennas are mounted on the satellites, typically with a diameter of a few meters up to 30 m [1,2]. To reduce the satellite payload, components such as reflectors, solar panels and satellite support structures are made of carbon fiber composites [3], where the reflectors commonly consist of multi-layer carbon fiber laminates. However, a reflector with a large aperture to mass ratio may suffer from high acoustic loads at take-off due to a wide range of airborne acoustics and structure-borne vibration interactions, potentially causing fractures. One way to overcome this problem is to utilize ultra light weight reflectors [2,4–6], which typically consist of a porous carbon fiber weave structure kept in place by a stabilizing rim. This type of "mesh reflector surface" is also commonly used in large aperture unfurlable reflectors [7,8], with a diameter up to 30 m, that are unfolded and deployed when the satellite is in position in space.

The high porosity of this type of reflectors implies a slight degradation of the electromagnetic reflection performance, but also provides a significant improvement of the payload and reduced acoustic loads of the structure at take-off compared to traditional reflectors. This property of triaxial carbon fiber weaves has been utilized in other applications such as face sheets in acoustic absorbing panels for aircraft engines [9]. The mechanical and thermodynamic properties of triaxial woven fabrics have previously been studied extensively [7,10,11]. However, to the knowledge of the authors, there are few previously published works where the acoustic and electromagnetic properties of this type of structures are ana-

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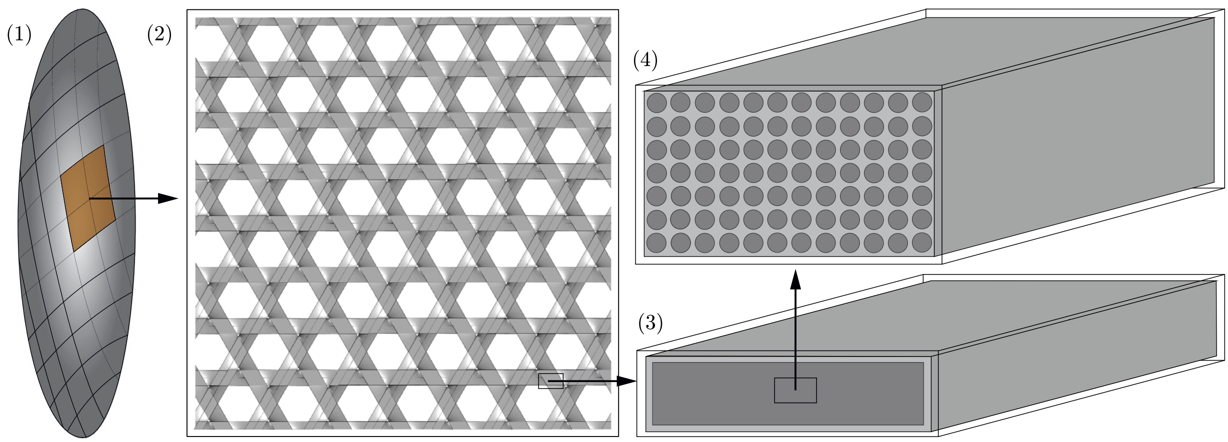

Fig. 1. Different length scales of an ultra lightweight weave reflector. The reflector surface (1) consists of a composite triaxial weave (2), where each of the weave fiber tows consist of a conducting core and an insulating coating (3). The conductive core is composed by many conductive microscopic fibers held in place by an insulating resin background material (4).

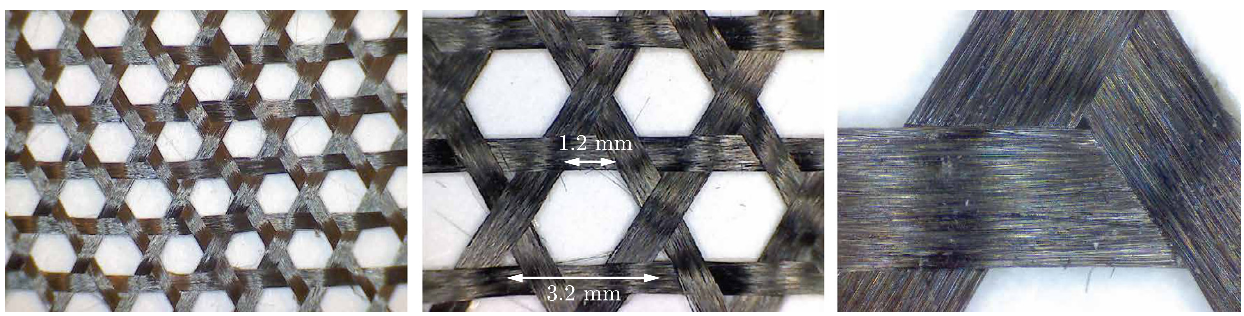

Fig. 2. The weave fabric under study, manufactured by Sakase Adtech [13], presented on three length scales.

lyzed in parallel, resulting in common design guidelines for triaxial weaves in satellite communication applications.

The outline of this paper is as follows: in Section 2 the general properties of the studied structure, the triaxial composite weave, are described. In Section 3 the electromagnetic reflection properties of the weave structure are investigated. In the low frequency limit the electromagnetic properties of the structure can be modeled using homogenization methods, while at the main frequencies of interest for satellite communication applications (the K_u and K bands at 10–30 GHz), the electromagnetic response of the structure is analyzed using full wave finite element method (FEM) simulation models. In Section 4 the acoustic properties of the weave structure are studied. A numerical model is established in order to study the impact of the mesoscale geometry, i.e. of a geometrical unit cell, on the fluid–structure coupling. Although fluid–structure interactions due to macro-scale properties play an important role, the study of flow resistance of the triaxial composite weave provides a major starting point linking the design parameters (unit cell geometry), the acoustic loading, and the acoustic excitation level. A parametric study of this flow resistance is thus presented, leading to a non-linear law accounting for medium to high sound pressure levels. In Section 5 design guidelines are presented based on the multiphysics considerations and the necessary tradeoff between the electromagnetic and acoustic performance of the structure. Finally, in Section 6 some concluding remarks are presented.

2. Triaxial weave structure

A porous weave reflector can be analyzed at different length scales, see Fig. 1. The microscopic fine structure of the weave consists of carbon fiber bundles (commonly referred to as fiber tows) in a background resin material, typically epoxy. Each fiber bundle is coated by an insulating resin coating such that the weave fiber tows are not in electric contact with each other. This further means that the weave fiber tows are only conductive along the fiber direction. The triaxial weave reflector surface used as a reference design in this study is manufactured by TenCate advanced composites [12]. The carbon fiber fabric consists of a pitch based high modulus fiber material made by Sakase Adtech in Japan, with the product reference YSH-70A 1K, and with a weight of 85 g/m^2 and a density of 0.59 g/cm^3 [13], see Fig. 2. The period of the weave pattern is approximately 3.5 mm and the side length of the perforations is about 1.2 mm, which corresponds to a perforation rate of 44%. The insulating resin is a cyanate ester RS-3C with low electromagnetic loss tangent [14], and the resin content of the reflector surface is approximately 28%. The manufacturing procedure of the triaxial weave fabric is based on braiding of multiple carbon fiber tows in three principal directions [15], and the manufacturing of the porous reflector surface from a braided weave is described in detail in [7].

The weave structure and its external loads are periodic and can thus be modeled by a unit cell geometry with periodic boundaries in the plane of the structure. In this paper two simulation models have been implemented to analyze the electromagnetic and acoustic properties of the weave: A detailed anisotropic weave model, taking into account the structure of the weave fiber tows, as in Fig. 3, and a simplified homogeneous slab model, as can be seen in Fig. 4. The size of the smallest possible unit cell that can be used to model the weave depends on the weave geometry and the nature of the considered problem. For example, when modeling the electromagnetic response of the structure, the vector-valued nature of the problem implies extra constraints to the unit cell modeling, compared to the analysis of scalar-valued acoustic interactions.

The width of the fiber tows is related to the unit cell parameters a and b in Fig. 4 as $w = \sqrt{3}(a - b)$, which implies that by