Investigating process technologies for production of carbon composite material antennas for maritime radio communication systems

N A Dugin, Yu S Fedosenko, G R Belyaev and E N Myasnikov
Volga State University of Water Transport, 603950, Russia
Nizhny Novgorod, Nesterov Street 5, 603950, Russia

Abstract. The paper is dedicated to studying manufacturing prospects of antenna devices from carbon composite materials and suggests technical solutions aimed at water transportation radio communication needs. Principal physical parameters of the carbon composite material used in manufacture and subsequent studies of antenna specimens were compared to those of metals. Peculiarities of manufacturing carbon composite antenna devices have been considered. Antenna specimens were experimentally studied for their electromagnetic characteristics, while their digital copies were studied in simulation. Similarities are pointed out between the main characteristics of composite antennae and their metal analogs. Efficiency of proposed technical solutions and antenna building technologies are demonstrated for application of carbon composite antennas in marine radio communication.

1. Introduction
Antennas are widely used in the modern communication and data transmission devices used in water transport [1]. The main structural material for their elements are various metals, which may sometimes lack corrosion resistance and thermal stability [2]. Construction of antenna systems (radiating elements) is associated with resolving issues in provision of mechanical rigidity, which influences both quality and stability of electromagnetic parameters. Considering these circumstances is rather important for marine vessel communication systems, as they are operated in aggressive water-air saline environment and are subjected to corrosive processes, high wind loads, significant temperature differentials and icing. Due to that, there is an ongoing search for alternative materials, which shall be light, strong, resistant to water-air saline environment, having stable characteristics across a wide range of temperatures, thus providing required electromagnetic parameters of antenna system operating components in a given frequency range.

2. Proposed technical solutions
Currently, glass reinforced plastics and carbon composite materials are used in antenna construction to build lightweight designs and reflective surfaces of reflector antennas, but they lack necessary electric conductivity [3, 4]. Epoxy binder serving as a component of such materials is not conductive and thus, in order to provide operability of such systems, carbon composite surfaces of antennas are metalized [5-7]. This technical solution imposes a number of constrains on operation of the antenna device in question in water-air saline environment, as mechanical attacks present in such conditions will lead to intensive corrosion damage of the thin conductive metallic layer and deterioration of the antenna’s electromagnetic parameters.
In order to increase stability of operation and resolve the stated issue, we suggest using carbon-fiber reinforced plastics (CFRP) [8-10]. By their specific strength and rigidity, CFRPs surpass most of regularly applied metal and polymer materials; their resistance against thermal shock opens prospects for their application in marine transport.

After analysis of physical characteristics of CFRPs available in the market, we selected the PX35 composite produced by Zoltek [11]. In order to evaluate the efficiency of its application to antenna construction, we conducted a comparison of its main parameters with those of two metals most often used for antenna element construction, namely, brass and aluminum. The principal characteristics of the materials are shown in Table 1. From the tabulated data, it is evident, that the prospects of applying CFRPs in antenna design are supported by their better thermal stability, mechanical strength and reduced specific weight in comparison with metals.

Table 1. Comparison of principal characteristics between CFRP Zoltek PX35 and metals.

| Parameter                      | Zoltek PX35 | Brass | Aluminium |
|--------------------------------|-------------|-------|-----------|
| Tensile strength (MPa)         | 4137        | 450   | 100       |
| Tensile modulus (GPa)         | 242         | 100   | 75        |
| Density (kg/m³)               | 1810        | 8500  | 2700      |
| Electrical resistivity (Ohm-m) | 15.5·10⁻⁶   | 0.06·10⁻⁶ | 0.028·10⁻⁶ |
| Linear thermal expansion       | 0.08·10⁻⁶   | 19.1·10⁻⁶ | 23.8·10⁻⁶ |
| coefficient (1/°C)            |             |       |           |
| Decomposition temperature (°C) | >650        | 880—950 | 650       |

From Table 1 it is also evident that there is a difference in conductivity between the materials in question, thus model simulation was conducted in order to study a dependence of antenna gain on conductivity of its material [12]. The obtained characteristic of conductivity $\rho$ for a designed digital copy of a C-range horn antenna is shown in Figure 1 as a solid line.

Figure 1. The G characteristic of a horn antenna as a function of its material resistivity.

The vertical dash line shows the $\rho$ value of the PX35 CFRP, a dash-and-dot vertical line shows the $\rho$ value of aluminum and a vertical dotted line shows the $\rho$ value of copper.
Analysis of antenna gain $G$ as a function of antenna material conductivity shows that at a specific resistance equal to that of PX35, the antenna gain falls insignificantly (by a few percent), which allows recommending it to be used in design of new antenna devices.

At the same time, there is a task of manufacturing complete surfaces of antenna devices from conductive CFRP. It is suggested to provide rigid fixation of carbon fibers in epoxy binder by means of graphene-like structures: nanotubes, appearing as fine black powder. Such structures have maximum mobility of charge carriers among known materials, making them prospective component for designing high-conductivity structures.

3. CFRP antenna manufacturing methods

The authors studied two process schemes for production of reflector aerial dipoles: by circular winding (a) and longitudinal laying (b) of CFRP onto non-conductive base serving as a blank of the radiating element (Figure 2).

![Figure 2. Process schemes of CCM dipole manufacturing](image)

CFRP reflectors were also produced by two methods: out of thread and out of fabric. The thread was wound onto the non-conductive blank in a single direction in such a way that the fibers are parallel to each other. When reflector was produced out of fabric applied onto a similar non-conductive blank, its fibers were perpendicular. Reflector produced from thread is shown to the left in Figure 3; the one to the right in the same Figure 3 has its reflector produced from fabric with CFRP dipoles. Manufacture of the radiating elements has been described in detail in [13, 14]

![Figure 3. External view of the CFRP reflectors.](image)

Fixation of CFRP thread and fabric in all cases was by means of graphene-infused epoxy binder. Measurements of electromagnetic characteristics were conducted in the laboratory following standard techniques [15]. Standing-wave ratios (SWR) and radiated pattern (RP) for CFRP and metal
antennas at a frequency of 530 MHz obtained experimentally and by simulation modeling on digital copies are shown in Figures 4 and 5 respectively.
- metal reflector and metal dipoles (solid line);
- CFRP reflector and metal dipoles (double solid line);
- metal reflector and CFRP dipoles with longitudinal laying (dashed line);
- CFRP reflector and CFRP dipoles with longitudinal laying (double dashed line);
- metal reflector and CFRP dipoles with circular winding (dash-and-dot line);
- CFRP reflector and CFRP dipoles with circular winding (double dash-and-dot line);
- results of modeling an antenna completely made of metal are shown as a solid line with a square marker.

Experimental results show that antennas with CFRP dipoles are characterized by a reduction of $G$ by up to 20% depending on combination of elements. This discrepancy is due to a difference in contact resistance at CFRP-metal contacts and roughness of the working surface.

![Figure 4. SWR characteristics of 530 MHz antennas obtained experimentally and by modeling.](image)

![Figure 5. Radiation pattern antennas characteristics at 530 MHz frequency from various materials obtained experimentally and by modeling.](image)

Experimental specimens of horn antennas were produced from CFRP and studied. Their production involved graphene-like structures in epoxy binder. The antennas were intended for operation in two frequency ranges: at a central frequency of the $L$ range at 1.6 GHz and at a central frequency of the $C$ range at 5 GHz [15].
Antenna for the $L$ range was manufactured exclusively out of CFRP thread by circular winding on a blank. Experimental research has shown that the antenna has electromagnetic parameters close to its all-metal analog. The difference in semi-width of approximated $RP$ between the all-metal and CFRP antennas amounted to about 7%, which is within the measurement error for antenna parameters in the laboratory.

Two antenna specimen were developed for operation in the $C$ range: one from Zoltek PX35 CFRP thread, another from CFRP fabric. Figure 6 shows CFRP antennas and their metal counterpart.

![Figure 6. C-band horn antennas made from CFRP and metal.](image)

SWR as a function of frequency is shown in Figure 7, while $RP$ diagrams are shown in Figure 8. The characteristics are marked with:

- solid line (metal antenna);
- dashed line (CFRP fabric antenna);
- dash-and-dot line (CFRP thread);
- solid line with a square marker (simulation modeling results).

![Figure 7. C-band antennas SWR.](image)
The SWR graph as a function of frequency for metal antenna shows a resonance nature, while for CFRP antennas this characteristic has been smoothed out, independent of manufacture method and CFRP structure. Similarly to dipole antennas, simulation modeling has not shown a reduction in G or worsening of SWR over the operating frequency range for CFRP antennas in comparison to metal ones. The characteristic obtained during simulation modeling is also somewhat different from the experimental characteristic diagram in the lower and upper frequency range. This is due to features of antenna feeder unaccounted in simulation; the feeder was represented by two orthogonal dipoles with a relatively narrow operating band. Distorted characteristic of the simulated specimens may be explained by contact resistance at metal-CFRP contact and operating surface roughness.

Thus, CFRP horn antennas with graphene additives are operable and demonstrate electromagnetic characteristics close to those of their metal analogs.

4. Conclusion
Experimental results and simulation modeling of electromagnetic characteristics of reflective dipole and horn antennas has shown prospects for using CFRPs together with a graphene-infused epoxy binder for production of marine communication antennas. Application of such materials will allow increasing reliability of data transmission in the context of severe air-water environment common for water transport.

References
[1] Haifeng Z, Mingchinq J and Guoqiang L 2015 Evolution of satellite communication antennas on mobile ground terminals Hindawi Publishing Corporation International Journal of Antennas and Propagation 2015 436250
[2] Straw R D, Severns R, Beezley B, Hare E, Bloom S, Morin J, Nelson S, Pingree D and Costa J 1997 The ARRL antenna book (Newington: The American Radio Relay League Inc.)
[3] Nicholson K J, Callus P J 2010 Antenna patterns from single slots in carbon fibre reinforced plastic waveguides Air Vehicles Division Defence Science and Technology Organisation 2389

Figure 8. C-band antennas RP diagrams.
[4] Artner G, Langwieser R and Mecklenbruker C F 2017 Carbon fiber reinforced polymer as antenna ground plane material up to 10 GHz. 11th European Conference on Antennas and Propagation (EUCAP) (Paris) pp 3601–3605
[5] Geterud E, Bergmark P and Yang J 2013 Lightweight waveguide and antenna components using plating on plastics 7th European Conference on Antennas and Propagation (EuCAP) (Gothenburg) pp 1812–1815
[6] Asao H, Yoneda N, Mukuda M and Yamasaki K 2003 Metal-plated plastic waveguide filter using injection molding process IEEE MTT-S Int. Microwave Symposium Digest 2 941–944
[7] Shelley M, Dang N 1998 Use of metallised plastics in high volume antenna applications low cost antenna technology IEE Colloquium (London) pp 7/1–7/5
[8] Bojovschi A, Knott G, Viquerat A, Nicholson K J and Tu L 2020 Carbon fibre reinforced polymer materials for antennas and microwave technologies Carbon-Related Materials pp. 45–63
[9] Cheng J 2000 Design of carbon fiber composite antenna dishes Proc. SPIE 4015 Radio Telescopes
[10] Thomassin J M, Jeromea C, Pardoeb T, Bailly C, Huynen I and Detrembleur C 2013 Polymer/carbon based composites as electromagnetic interference (EMI) shielding materials Materials Science and Engineering: Reports 74(7) 211-232
[11] Zoltek Px 35 technical list, Retrieved from: https://zoltek.com/products/px35/.
[12] Tunakova V, Gregj J 2010 Electrical conductivity measurement of fibers and yarns Proc. of Texsci: 7th International Conference Textile Science TEXSCI 2010 (Liberec: Technical University)
[13] Dugin N A, Zaboronkova T M, Krafft C and Belyaev G R 2020 Carbon-based composite microwave antennas (Review). MDPI Electronics 9 590-1–590-17
[14] Dugin N A, Zaboronkova T M, Myasnikov E N and Belyaev G R 2018 Electrodynamc characteristics of horn microwave antennas made of graphene-containing carbon-composite materials Technical physics 63(2)
[15] IEEE Std 149-1979 IEEE standard test procedure for antennas