Storaged mechanical energy in electromecanical flywheels with different relations of carbon fiber as reinforcement

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Abstract. The work presents a study focused on a specific type of inertia wheel, known as Flywheel, capable of accumulating kinetic energy when in motion. Computational analyzes were performed on the geometry and proportion of conjugate materials to the rotor in order to obtain the largest rotational energy accumulation. This study aims at analyzing a rotating inertia wheel at a rotational speed greater than 100,000 rpm, thus concentrating more energy and reducing material dimensions and costs. For this purpose, several types of inertia wheel geometries were created and simulated by the Finite Element Method, with the intention of verifying the behavior of the tensile strengths of the material at its high rotation speed. With these data, it was chosen the geometry and the material that together obtained the best performance for the development of an inertia wheel of low cost and high energy yield, with rotations obtained above 170,000 rpm.

1. Introduction

The concept of electromechanical battery dates back to the 1940s, when a new electric bus model, Gyrobus \cite{1}, was developed and implemented. The system consisted of a flywheel with mass of 1,500 kg, 1,600 mm diameter in a sealed chamber filled with hydrogen, pressure of 70 kPa and a maximum speed of 3,000 rpm.

To use the flywheel as an electromechanical battery, the principle of operation is very simple: it is basically to put a wheel to rotate in situations where it is not subject to great losses of energy with friction or any other action outside \cite{2}. It is an extremely simple way of storing mechanical energy, in which it easily converts mechanical energy into electrical energy and vice versa, using a simple electric generator motor.

With the technological development taking place in the various fields of engineering, new uses of the flywheel began to be studied, as well as new constructive and conceptual forms, including the advent of new requests of the equipment. The proposal of a flywheel with a large mass evolved into a smaller mass flywheel, but with a much higher speed \cite{3}.

The electromechanical battery has a wide field of application, among them: emergency installations, industrial installations, power plants, elevators and cranes, regenerative brake and hybrid vehicles \cite{4}.
Table 1. Tensile strength of selected materials.

| Material          | Density (g/cm$^3$) | Ultimate tensile strength (MPa) | Yield strength (MPa) |
|-------------------|---------------------|----------------------------------|----------------------|
| Maraging steel    | 8.08                | 2451                             | 2395                 |
| AISI 18Ni 350     |                     |                                  |                      |
| Carbon fiber      | 1.87                | 3730                             | 3500                 |
| Hexcel UHM 12,000 F |                    |                                  |                      |

This analysis prioritized the highest volume of steel with the lowest possible volume of carbon fiber, since the density of Maraging steel has a value greater than the density of carbon fiber, as evidenced in Table 1, which would contribute positively for the performance of the equipment.

The carbon fiber had the specific function of maintaining the structural integrity of the rotor, but despite the essential function mentioned, it impairs the performance of the equipment due to the deficiency of kinetic energy accumulation because of the value of its density. Thus, the conjecture indicated a volume of carbon fiber reduced to the minimum permissible to maintain the integrity of the mounting in the high demands resulting from the accelerations and desired speeds, with the consequent greatest volume possible, and with its directly proportional mass of Maraging steel.

2. Methodology

Engineering designs have long existed as a means of defining a product graphically before it is made and used by consumers. The use of CAD (computer aided design) or CAE (computer aided engineering) software is justified when the geometry of the parts is complex or the interaction of different materials is involved. Finite element analysis of complex parts through software makes the results accurate. The results are graphically demonstrated allowing visual identification of the geometry and results, facilitating the interpretation of what is occurring in the part or set.

For this work, it was used SOLIDWORKS [5], which is currently one of the main softwares of computer graphics and finite element modeling. We took advantage of the experience gained with the work in simulation by finite elements that can be seen in previous articles [6–11] in which the results are validated using experimental data or by properties of symmetry of the problem.

The different relationships between the rotor constituent materials were analyzed, aiming at the optimization of the mass/integrity ratio, that is, a rotor with the largest possible mass, to obtain, directly proportional, the greatest moment of inertia [12].

For the analysis using conjugate materials, i.e., a Maraging steel core coated with carbon fiber, a standard geometry was used. The carbon fiber coating aims at a performance gain of the rotor assembly, with greater capacity of energy accumulation by the rotor. The analyzed proportions, shown in Figures 1 and 2, had standard measures of diameter and height for calculations and simulations, varying the relationship between carbon fiber thickness and Maraging steel.

This model presented as critical point the ends of the crown away from the disc. This behavior was verified both in the analyzes carried out in Maraging steel and in the analyzes performed with carbon fiber.

The stress concentration in this section limited the study to a maximum rotation of 65,290
Figure 1. Rotor in section.

Figure 2. Rotor dimensions given in mm.

Figure 3. Result of rotor analysis in Maraging steel. The von Mises stress color scale is given in Pa.

rpm when the analyzes were performed with Maraging steel, and 162,450 rpm with the analyzes performed with carbon fiber.

The simulations were restricted by the rotor dimensions; its height and its diameter remained the same in all trials. Thus, the 200 mm rotor diameter was preserved in all simulations and, in order to perform the carbon fiber simulations, whenever the carbon fiber was added to the rotor, the same volume of Maraging steel should be removed from the rotor.

3. Results
The carbon fiber coating added to the rotors allows the increase of the maximum speed supported by the rotors, changes the stress concentration and contributes positively to the improvement of the performance of the rotors, as can be observed in the results of the simulations.

The comparison between the analyzes performed with the 95 mm radius Maraging steel rotor without carbon fiber (Figure 4) and the same conjugate rotor of Maraging steel and carbon fiber with a thickness of 5 mm (Figure 5) shows that there was a change in the rotor behavior. The stresses that have limited the study and have been concentrated on the inner ends of the crown move to the interface between the carbon fiber and the Maraging steel, demonstrating the action of the carbon fiber in the set.
Figure 4. Analysis of the rotor with radius of 95 mm in Maraging steel without coating. The von Mises stress color scale is given in Pa.

Figure 5. Analysis of the Maraging steel rotor with 5 mm carbon fiber coating. The von Mises stress color scale is given in Pa.

The comparison between the analyzes carried out with the 85 mm radius Maraging steel rotor without carbon fiber (Figure 6) and the conjugate rotor of Maraging steel with a radius of 85 mm and carbon fiber with a thickness of 15 mm (Figure 7) showed a pattern in the change of the rotor behavior. The stresses that have limited the study and have been concentrated on the inner ends of the crown move to the interface between carbon fiber and Maraging steel, and no longer limit the study, demonstrating the action of the carbon fiber on the set. The stresses that limit the study are now concentrated around the rotor axis.

In Figure 8, the physical aspect of the rotor is shown with the addition of 30 mm thick carbon fiber coating.

The comparison between the analyzes performed with the 70 mm radius Maraging steel rotor without carbon fiber (Figure 9) and the conjugated rotor of Maraging steel with a radius of 70 mm and carbon fiber with a thickness of 30 mm (Figure 10) characterizes the change of the rotor behavior by the action of the carbon fiber. The stresses that have limited the study and have been concentrated on the inner ends of the crown move to the interface between carbon...
Figure 6. Analysis of the rotor with 85 mm radius in Maraging steel without coating. The von Mises stress color scale is given in Pa.

Figure 7. Analysis of the Maraging steel rotor with 15 mm carbon fiber coating. The von Mises stress color scale is given in Pa.

Figure 8. Rotor coated with a 30 mm thickness carbon fiber.
Figure 9. Analysis of the 70 mm radius rotor in Maraging steel without coating. The von Mises stress color scale is given in Pa.

Figure 10. Analysis of the Maraging steel rotor with 30 mm carbon fiber coating. The von Mises stress color scale is given in Pa.

fiber and Maraging steel, and no longer limit the study, demonstrating the action of the carbon fiber in the set. The stresses that limit the study are now concentrated around the rotor axis. Figure 11 shows the maximum rotation increase provided by the action of the carbon fiber on the rotors.

4. Conclusions
The performance of the Maraging steel and carbon fiber conjugated rotors was superior to the same rotor without the carbon fiber coating. These results were evidenced and are reproduced in Table 2. When compared to the rotor composed of one of the two materials, only of Maraging steel or carbon fiber, its performance was below expectations. This performance is evidenced in the comparison in Figure 12.

The behavior observed in Table 2 and Figure 12 was not initially expected because, although the mass of the rotor is reduced with the increase of the carbon fiber fraction in the constitution
of the set, it was expected that the increase of the rotation speed would provide an increase of the rotational energy, which was not verified in the simulations.

This work is still under development and new stages should be presented in future publications.

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Table 2. Values obtained for maximum rotation and rotational energy.

| Rotor (configuration)                          | Rotation (rpm) | Rotational energy (J) |
|-----------------------------------------------|----------------|-----------------------|
| Rotor with radius 100-65, Maraging steel       | 68,090         | 2,962,688.00          |
| Rotor with radius 100-65, carbon fiber         | 170,970        | 4,323,039.97          |
| Rotor 95-65 - only steel core                  | 69,780         | 2,483,016.71          |
| Rotor 95-65 - Steel core with 5 mm coating     | 72,350         | 2,825,669.00          |
| Rotor 90-65 - only steel core                  | 70,800         | 2,003,554.65          |
| Rotor 90-65 - Steel core with 10 mm coating    | 76,700         | 2,677,239.00          |
| Rotor 85-65 - only steel core                  | 71,020         | 1,545,342.92          |
| Rotor 85-65 - Steel core with 15 mm coating    | 82,280         | 2,505,401.00          |
| Rotor 80-65 - only steel core                  | 70,660         | 1,139,148.28          |
| Rotor 80-65 - Steel core with 20 mm coating    | 88,800         | 2,548,942.00          |
| Rotor 75-65 - only steel core                  | 69,510         | 789,013.33            |
| Rotor 75-65 - Steel core with 25 mm coating    | 96,160         | 2,528,072.00          |
| Rotor 70-65 - only steel core                  | 67,740         | 505,668.24            |
| Rotor 70-65 - Steel core with 30 mm coating    | 103,460        | 2,489,615.35          |

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