ABSTRACT

Small satellites for earth observation missions have received attention in the recent years for further optimisation. A potential approach would be to optimise the existing platforms in order to cope with their increasing mission requirements (e.g. mass, volume, etc.). In this article, the idea of combining the energy storage and attitude control systems is presented based on the flywheel technology, (combined energy and attitude control system, CEACS). Such a system consists of a double counter rotating flywheel assembly serving simultaneously for the satellite energy and attitude management. First, numerical treatments are conducted for the CEACS rotor to determine a failure free operational speed corresponding to the rotor stresses and natural frequencies. Then, the mathematical model describing the energy and attitude control is established, and the CEACS onboard architecture is implemented. Further, numerical simulations for the developed architecture are performed for the ideal and non-ideal test cases. This end-to-end system demonstration indicates that the CEACS is judiciously feasible, and is a potential subsystem for the future small satellites.

1. INTRODUCTION

Generally, the CEACS consists of high speed composite rotors, magnetic bearings, motors/generators, and control electronics for the energy/attitude management. With a double counter rotating flywheel assembly, the CEACS can be employed for the satellite energy storage and attitude control. In this article, the concept is investigated exclusively for small satellite missions, e.g. for earth observation. The novelty in the present work lies in the introduction of the CEACS energy and attitude control architecture in a torque control mode, an analysis of the CEACS rotor stresses incorporating the natural frequencies, and the demonstration of the formal CEACS end-to-end system performance.

2. FLYWHEEL ROTOR

For an illustration of the investigation, a reference mission is selected for a small satellite. Important mission constraints are: 50 kg satellite with $0.5 \times 0.5 \times 0.5$ m$^3$ of volume, 3 years of mission duration, a circular orbit at 500 km with an inclination of 53°, pitch axis attitude requirement $< 0.2^\circ$, and 35 W of power requirement. First, the
rotor design is implemented according to Sung [1]. The available literature on the rotors are radically focussing on the stress analysis. The natural frequency analysis for the rotors were not incorporated. For CEACS, the triple layer composite rotor design is selected, which is presumably much stronger than the single layer rotor design in the high speed regimes [2]. Various material compositions have been investigated to obtain the best recipe for the triple layer rotors. The numerical treatments (3D rotor dynamics- ANSYS™) were carried out to determine the rotor stress distributions (e.g. at 50 000 rpm). The natural frequency (rotor mode shapes) analysis was also performed, which is based on the equation of motion for free vibrations without the damping term. The optimised rotor consists of a good longitudinal strength carbon fibre at the inner rim (25 % T800H/2500), followed by a high radial strength carbon fibre (15 % AS4/APC2 Carbon/PEEK), and finally a high longitudinal strength carbon fibre (60 % Generic IM6/Epoxy) at the outer rim. The optimised inner and outer radii for the reference mission are $R_i = 0.1106 \text{ m}$ and $R_o = 0.1230 \text{ m}$, respectively, and with a rotor height $h$ of $0.0183 \text{ m}$. The 2D longitudinal stress distribution is shown in Fig. 1 (a). The maximum tensile stress in the third layer is lower compared with the usable longitudinal tensile strength of Generic IM6/Epoxy (2275 MPa). The inner and middle rotor layers experience tensile stresses of about 500 MPa, which are below the usable longitudinal tensile stresses of the materials, 1885 MPa (T800H/2500) and 1385 MPa (AS4/APC2 Carbon/PEEK), respectively. Therefore, failure-free conditions are achieved in the fibre direction. On the other hand, the 2D radial rotor stress distribution is depicted in Fig. 1 (b). The maximum tensile stresses of about 0.3 MPa appear in the inner and outer layers. However, these stresses are well below the usable radial tensile strength of T800H/2500 (39.2 MPa) and Generic IM6/Epoxy (29.68 MPa). The middle layer, AS4/APC2 Carbon/PEEK, experiences a maximum compressive stress of about 4 MPa, which is quite low compared with its usable radial compressive strength (106 MPa). Thus, failure-free conditions are achieved in the radial direction as well.

![Figure 1: Rotor Stress Distributions](a) (b)

Actually, the rotors were tested for a speed of about 45 000 rpm first. It was found that the maximum stresses and the natural frequencies are not critical at 45 000 rpm. Then, the test case was extended for a rotor speed of 50 000 rpm. The first natural frequency appeared at 46 019 rpm. Thus, the CEACS rotors should be operated below this speed.
3. CEACS CONTROL ARCHITECTURE

The CEACS control architecture is presented in Fig. 2. The dynamics for the flywheel system in Fig. 2 simplifies to:

\[ \frac{T_S}{u} = 2K k_m. \]  

(1)

Denoting \( s \) the Laplace variable and defining \( F(s) = \frac{1}{1 + \frac{K_D}{K_P} s} \), the transfer function for the satellite’s dynamics yields:

\[ \frac{\theta_{sat.}}{\theta_{ref.}} = \frac{1}{1 + \frac{K_D}{K_P} s + \frac{I_{sat.}}{K_P} s^2}. \]  

(2)

Figure 2: CEACS Control Architecture. \( T^{S/w1} \) and \( T^{w1/S} \) are the projection matrixes with a scalar value of 1. And, \( T^{S/w2} \) and \( T^{w2/S} \) have a scalar value of –1. The moments of inertia for both flywheels and the corresponding time constants, and the other constants are held equal, i.e. \( k_m = k_{m2} = k_m \), \( I_{w1} = I_{w2} = I_w \), and \( K_1 = K_2 = K \). Also, let \( 2K k_m = 1 \) such that \( T_S/\theta = 1 \), and the motor torque constant \( k_m = 1 \) is assumed.

4. CEACS PERFORMANCE

The system is designed to store about 21 Wh of energy to fulfil the reference mission’s energy demand during the eclipse phase. The flywheels are mounted on the pitch axis of the satellite, and are requested not only to keep the pointing accuracy of the axis below 0.2 ° but also to provide a minimum bias momentum of about 240 rad/s for the roll/yaw axis stiffness. Two test cases were numerically treated (Matlab-Simulink™), namely the ideal and the non-ideal CEACS. The first test case assumes an ideal system without considering any internal disturbances, taking into account only the external disturbance torques acting on the satellite. The proportional and derivative attitude control gains selected are \( K_P = 0.0086 \) Nm/rad and \( K_D = 0.1983 \) Nms/rad, respectively. In Figs. 3 (a) and (b), the flywheels’ speeds increase during the charging phase and decrease during the discharging phase. And, Fig. 3 (d) shows that the satellite energy demand (≈ 21 Wh)
during the eclipse phase is supplied by the system. Additionally, the attitude accuracy and the bias momentum remain within their required budgets, see Figs. 3 (e) and (c), respectively. For the non-ideal case, the system was tested for a relative motor/generator torque constant difference of 0.5 %, and a relative difference in flywheels’ inertias of 0.2 % [3]. Fig. 3 (f) shows the impact of these errors, which causes the attitude accuracy to exceed its pointing budget. However, the attitude accuracy can be improved by increasing the stiffness of the active control loop. Despite the internal disturbances, the non-ideal CEACS also fulfils the mission requirements. In fact, the non-ideal performances are similar compared with the ideal CEACS test results (e.g. flywheel speeds, energy stored, and bias momentum).

5. CONCLUSION AND OUTLOOK

The CEACS is a promising alternative to replace the conventional electrochemical batteries. Hence, the commissioning of CEACS on earth observation platforms would benefit the missions, e.g. life duration, reliability and performance enhancements, mass and volume savings, etc. In order to achieve the formal operational status, further research should be concentrated on designing a CEACS prototype.

6. REFERENCES