



# Novel repeatable launch locking/unlocking device for magnetically suspended momentum flywheel<sup>☆</sup>

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## ABSTRACT

Because one-shot launch locking/unlocking device (OSLLUD) cannot repeat locking/unlocking, and repeatable launch locking/unlocking device (RLLUD) has an insufficient reliability of implementing unlocking, a novel RLLUD consisting of a motor, wire rope and several same flexible brackets was proposed. The composition, operating principle and functional performance requirements were introduced. A single flexible bracket was equivalent to a cantilever beam-mass model, and its static and dynamic performances were analyzed. Design variables were selected according to the sensitivity analysis method. Unlocking force, the maximum stress and the first resonance frequency were concerned, and the flexible brackets were optimized through the comparison and the sequential quadratic programming methods. The RLLUD was manufactured according to the optimization results. The environmental mechanics tests of tri-axial swept-sine and random vibration were carried out to verify the protective effect of the novel RLLUD for magnetically suspended momentum flywheel (MSMFW) during launch. The results show that the maximum macroscopic vibration is less than the protection gap of the flywheel, and its locking protective effect is valid and sufficient.

## 1. Introduction

The momentum flywheels with ball bearings are used for tri-axial high precision attitude control in most spacecraft [1,2], and this solution has been considered as a mature and irreplaceable method over the last 30 years. Nevertheless, the application scenario has been changed by the magnetically suspended reaction or momentum flywheel. The magnetic bearings have distinctive advantages such as virtually zero wear, long service life, high control precision, low micro vibration and body noise, wide operational temperature range and so on [3–5]. Although magnetic bearings seem capable to hold the flywheel rotor during launch by electromagnetic forces, most available magnetically suspended momentum flywheels (MSMFWs) are equipped with an additional launch locking/unlocking device (LLUD) [6,7]. Therefore, the LLUD, magnetic bearing and drive motor can be regarded as the three core components of magnetically suspended momentum flywheel system [7,8].

The LLUD can be categorized based on the locking/unlocking times as one-shot launch locking/unlocking device (OSLLUD) [6,9–11] and repeatable launch locking/unlocking device (RLLUD) [12–15].

According to the manner of locking, the LLUD can be classified as inner-locking device [9,10,12–15] and outer-locking device [6,11]. The characteristics of all the devices are as follows:

- (1) Keeping locking through friction self-locking.
- (2) Implementing unlocking by means of elastic mechanism such as flexible bracket, spring and so on.
- (3) Keeping unlocking entirely or partly depending on elastic mechanism.
- (4) All OSLLUDs adopt pyrotechnic devices to implement unlocking.

Owing to the simple structure and high reliability of pyrotechnic device, the OSLLUD is valid considerably for the MSMFW [6,9–11]. The device consisting of conical bearings for locking and pyrotechnic part for releasing has been successfully used in spacecraft many times [16]. Livet and Bretaudeau [9] proposed an OSLLUD employing two conical emergency bearings to immobilize the inertia flywheel rotor. The friction self-locking and the reliable pyrotechnic device were used for keeping locking and implementing unlocking, respectively [9]. According to Livet and Bretaudeau [9], Beau et al. introduced a scheme

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based on the friction self-locking between screw and nut to keep locking, and unlocking was implemented through the pyrotechnic device cutting screw [10]. Michel et al. developed a pneumatic OSLUD to lock and clamp the rotor of MSMFW of SPOT4 satellite [6]. Furthermore, Rockwell Collins Deutschland GmbH developed another similar pneumatic device [11]. In the schemes above [6,9–11], the flywheel rotor was held through elastomeric tubes against launch vibration. The locking contact surface is wide, and the Hertz contact [17,18] does not occur in locking pair. Thus, both the fretting wear [19,20] and the fretting fatigue [21] were inhibited. The capability of multiple locking/unlocking is required for flywheel systems during transportation and tests on the ground.

To remedy the limitation of OSLUD, many RLLUDs with the repeatable work of locking/unlocking were proposed. Han et al. presented an electromagnetic RLLUD based on the friction self-locking of wedge [12]. By controlling the value and direction of coil current, the permanent-magnet flux was forward and reversely superposed by electromagnetic flux, and the flywheel system was locked and released in turn. Liu et al. introduced another electromagnetic scheme [15]. To increase the reliability of implementing unlocking, the external permanent magnet approach was replaced by internal approach. Utilizing the wedge friction self-locking component [12,15], Zhang et al. [13] and Yan et al. [14] proposed a RLLUD based on shape memory alloy as the actuator to lock and release flywheel system. The multiple locking can be implemented with manual intervention before launch. The rotor is released only by LLUD in orbit. Therefore, the flywheel system put very demanding requirements on the reliability of implementing unlocking. In repeated schemes above [12–15], the locking state is kept by friction self-locking, which has high reliability to keep locking. However, when the actuator like electromagnet in [12,15] and shape memory alloy in [13,14] is out of use, the flywheel rotor will not be released. Therefore, its reliability to implement unlocking is relatively insufficient.

In order to overcome the disadvantages of repeatable schemes mentioned above, this paper presented a novel RLLUD including flexible brackets, motor, screw-nut, spur and worm gear. These elements can be regarded as release, actuator, transmission and clamping mechanisms respectively. The composition, operating principle and function performance requirements of the device were presented. The static and dynamic analysis of flexible bracket was performed. According to the result, the part was optimized through the comparison method and the sequential quadratic programming method [22–24]. To verify the protective effect for MSMFW, environmental mechanics tests were carried out.

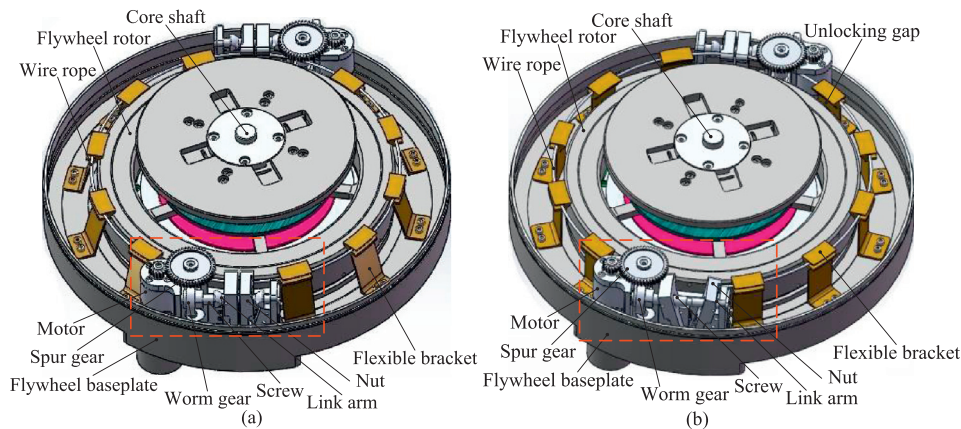


Fig. 1. Construction of RLLUD. (a) Locking; (b) unlocking.

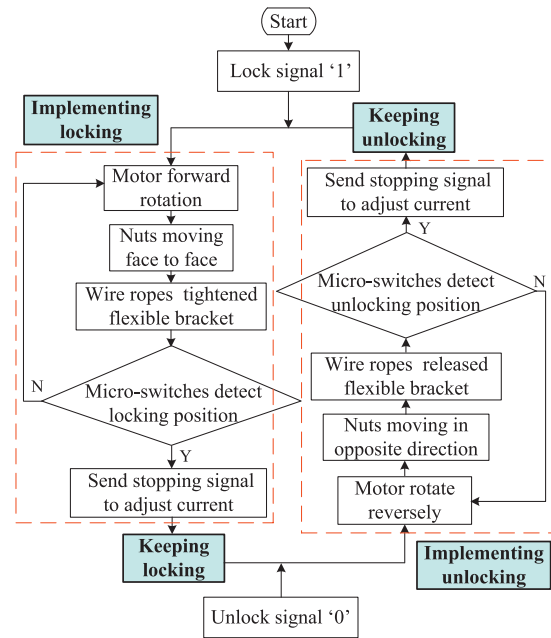


Fig. 2. Flow chart of RLLUD working.

## 2. Proposed RLLUD

### 2.1. Structure and operating principle

The novel RLLUD [25] is shown in Fig. 1, by controlling the direction of the current generated in motor coils, the wire rope is driven to tighten and release the flexible brackets, and the flywheel system is locked and unlocked. The device mainly consists of two motors, four spur gears, two worm gears, two screws, four nuts, two wire ropes, four link arms and several flexible brackets. These two wire ropes with equal length are joined end-to-end by the four link arms. Under locking state, two transmission mechanisms are in tension state. On the opposite, if one of the wire ropes is relaxed, the flywheel system will be released. Thus, to increase the reliability of implement unlocking, the two motors and transmission mechanisms are operated redundantly.

The work process of RLLUD can be divided into four steps, implementing locking/unlocking and keeping locking/unlocking. When receiving the lock signal '1', the two motors are supplied with the forward locking current. The two pairs of nuts are driven to move face-

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