DESIGN OF A NOVEL SEPARATION MECHANISM FOR HIGH-POWER MODEL ROCKETS

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ABSTRACT

In this paper, a novel separation mechanism designed for the EPFL Rocket Team's experimental sounding rockets is presented. This mechanism is a structural part of the vehicle, located close to its centre. At apogee, the separation allows for the deployment of parachutes through the mechanism. It is constructed around a spring steel clamp band assembly that can be opened by a new and simple burn wire release system, with a two-fold built-in actuation redundancy to ensure a reliable separation. The main development goals are the reduction of size, weight and cost, while keeping a simple manufacturing process. The mechanism is also designed with reusability and testability in mind. The system is presently undergoing a testing campaign and is foreseen to be launched at the end of July of 2021.

INTRODUCTION

The EPFL Rocket Team (ERT) [1] is a student association of the Ecole Polytechnique Fédérale de Lausanne (EPFL), in Switzerland. One of its goals is to engage students in the development of state-of-the-art high-power model rockets and participate in student rocketry competitions, such as the Spaceport America Cup (SAC) [2] or the European Rocketry Challenge (EuRoC) [3]. Every year, a new rocket is designed, built and launched by the team. The ERT currently competes in the 3'000 m altitude student research and development (SRAD) hybrid rocket motor category, with a 3.4 m long and 41.4 kg wet mass launcher, the Bella Lui II rocket (Fig. 1).

In order to be able to re-fly the rocket multiple times, and to satisfy one of the competition requirements, all the rocket parts need to be safely recovered after a controlled descent under parachutes. This derives the need of a separation mechanism, which is part of the first recovery event. It separates the rocket in two and allows the parachutes to be deployed.

Until now, the ERT rockets used a commercial of the shelf (COTS) compressed CO_2 ejection system [4] to separate the nose cone of the rocket. This design presented some issues in testability, repeatability and logistics due to the use of a black powder based pyrotechnic actuation.

Due to the structural weakness of this slide-in and shear pins system, the separation point was located at the base of the nose cone to minimize loads during flight. This location induces large forces on the parachutes' shock cords due to the weight asymmetry between the two rocket parts after separation.

All these disadvantages motivated the design of a new and stronger separation mechanism, which can be placed closer to the centre of the rocket.

REQUIREMENTS

The new separation mechanism requirements were set by the ERT's system engineers during the project definition, at the start of the academic year 2020 - 2021. The main design requirements are listed here:

- The design phase of the new separation mechanism shall be no longer than one academic semester (4 months).
- The separation mechanism shall have a reliable, two-fold redundant, actuation.
- The separation mechanism should avoid any compressed gas and pyrotechnic energy source.

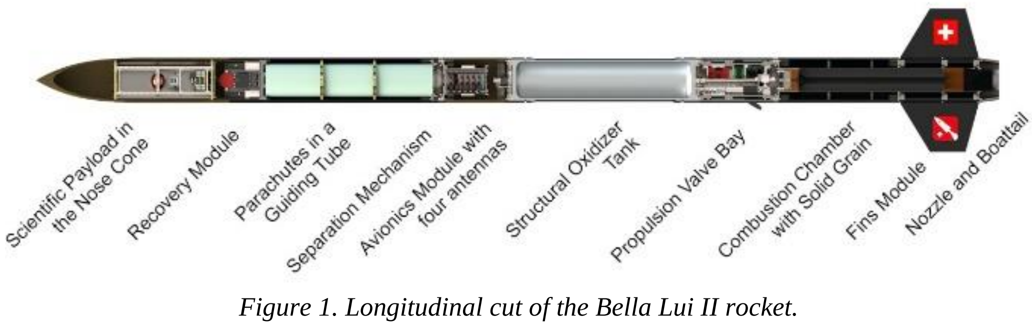

Figure 1. Longitudinal cut of the Bella Lui II rocket.

- The elapsed time between command and separation shall be no longer than 2 s.
- The separation mechanism shall have a smooth outer diameter of 156.7 mm, in the prolongation of the airframe.
- The separation mechanism shall have a free inner diameter of at least 110 mm.
- The separation mechanism should maximize the free inner diameter, allowing for the passage and ejection of the parachutes.
- The separation mechanism shall weight no more than 800 g.
- The separation mechanism shall be no longer than 60 mm.
- The separation mechanism should be assembled and integrated on the rocket by a maximum of two operators.
- Once assembled, the separation mechanism is a structural part of the airframe and shall withstand all the stresses experienced by the launch vehicle with a safety factor of 2.
- All the operations, including but not limited to the assembly, integration, and flight, shall be possible in a dusty, desert like, environment.
- The separation mechanism shall operate nominally for temperatures ranging from -10 °C to 80 °C.
- The separation mechanism shall be reusable.
- The separation mechanism shall be easily tested in various configurations.
- The separation mechanism shall be manufactured with standard ERT capabilities.

STATE OF THE ART

Most separation mechanism implemented in model rockets use compressed gas cartridges and/or a black powder based pyrotechnic separation energy source. As mentioned previously, due to the mechanical weakness of these systems, they have to be placed close to the rocket tip. Therefore, these designs are ruled out by the requirements listed above.
Large scale orbital rockets often use explosive blots/nuts, or other more complex separation mechanisms between the rocket stages. These systems have to deal with much higher loads than the ones encountered in high-power model rockets, such as Bella Lui II.
Loads in the same order of magnitude as the ones acting on a separation mechanism to be designed can be found in commercial satellite release systems. Some of these state-of-the-art products are made by RUAG Space with the "PAS" series of payload adapters and separation systems [5], and by Planetary Systems Corporation with the "Advanced Lightband" [6]. The key features of these systems are a low shock, low tip-off rotation rate and precise delta-V separation, essential for accurate orbit insertion.
These two systems are based on a clamp band like design and are the main inspiration for the separation mechanism presented in this paper. However, they are largely over-engineered for the ERT's application. The separation isn't required to be that precise and such parts could not be manufactured within the team's budget.

EXTERNAL LOADS

The loads acting on the separation mechanism are computed from the various accelerations experienced by the rocket during ground handling and flight (ascent only). These include a posigrade acceleration due to the motor thrust, a retrograde deceleration due to aerodynamic drag and gravity after motor burnout, and a radial acceleration.
The radial acceleration experienced in flight is not well known. This load is however exceeded on the ground during the "spaghetti test", which is a mandatory pre-flight check of the competition. In this test, the rocket is held by hand at the two ends and shaken up and down, inducing large bending moments along the rocket. The radial acceleration of the rocket during this test can be estimated and is given in Tab. 1.
The numerical values of all the accelerations and corresponding loads are also given in Tab. 1. The factor of safety (FoS) on all the loads is equal to 2.
The mechanism's internal forces were analysed separately for all the load cases mentioned above. These computations show that the bending moment due to radial acceleration is by far the most critical load.

Table 1. External accelerations and corresponding loads on the separation mechanism

Acceleration	Direction	Load type	Value	With FoS
10 g	Posigrade (thrust)	Compressive	1150 N	2300 N
10 g	Retrograde (drag)	Tensile	1150 N	2300 N
2 g	Radial	Shear	375 N	750 N
		Bending	305 Nm	620 Nm

FINAL DESIGN

The new separation mechanism is designed around a spring based clamp band system. An exploded view of the design is shown in Fig. 2. Its different parts are subsections below. The mechanism's overall dimensions are given in Tab. 2.
Most of the development time for the new separation mechanism was spent on the burn wire release system and on optimising the structural parts geometries with

Table 2. Main dimensions of the separation mechanism

Quantity	Value	Unit
Height (without gluing flange)	33.5	mm
Outer diameter	156.7	mm
Free inner diameter	116	mm
Total mass	605	g

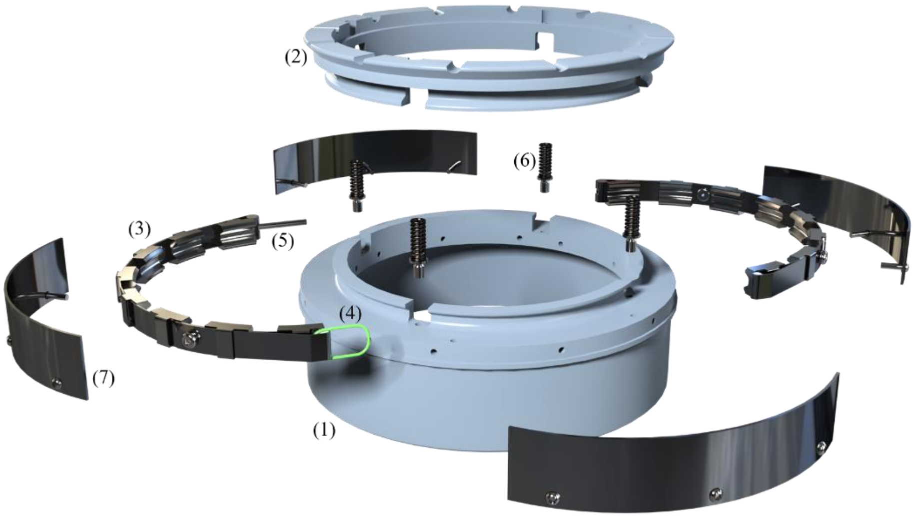

Figure 2. Exploded CAD render of the separation mechanism. (1) Lower ring, (2) Upper ring, (3) Clamp band half, (4) Dyneema loop of the burn wire release system, (5) Tensioning bolt, (6) Compression spring and guide, (7) Aero-cover.

respect to the available space (~20 mm on the radius) and the applied loads (Tab. 1), while keeping them as simple and compact as possible.

Lower ring (1)

The lower ring is made out of aluminium with an Ematal hard anodization surface treatment to reduce the friction coefficient and to reduce wear due to the contact with the clamps. This part is epoxy-glued in the carbon fibre reinforced polymer (CFRP) airframe tube on one side, and interfaces with the clamp band on the other side.

Upper ring (2)

The upper ring is similar to the lower ring and made of the same surface treated aluminium. It features a coupler interface instead of the gluing flange [7]. These couplers are used between all of the rocket's modules, allowing the separation mechanism to be coupled to any of them.
The implementation of the coupler greatly simplifies the assembly of the mechanism, without having to align the entire rocket. It also enables more testing possibilities with the mechanism experiencing various loads during the test (different coupled masses in different orientations). Tests without coupling are also possible.

Clamp band (3)

The clamp band is made of two symmetric halves, connected on one side by the burn wire release system and on the other side by a tensioning bold. The band is made out of a folded and riveted stainless spring steel sheet metal, which pulls back the clamp during the separation due to its elasticity.
The 16 clamps are made of solid stainless steel, with a surface roughness below Ra 1.6. The clamps have an opening angle of 60° (30° by side), therefore avoiding the self-locking of the clamps on the rings due to friction forces when the mechanism is under tension (for example due to drag).
The spring steel band is guided on the clamp by passing through U-shaped folded sheet metal brackets welded on the top and bottom of each clamp. This allows the band to slide over the clamps during the tensioning and ensures a uniform tension all around the mechanism.

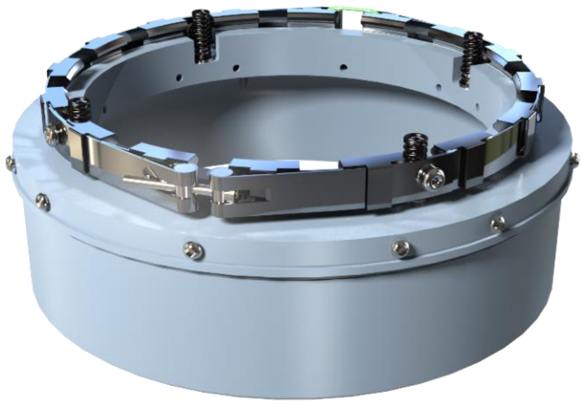

Figure 3. Partially assembled separation mechanism (no upper ring and aero-covers).

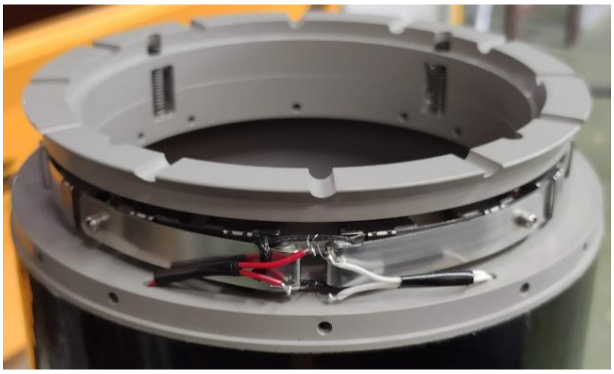

Figure 4. Redundant burn wire release system assembled on the uncoupled mechanism.

Burn wire release system (4)

The burn wire release system consists of a loop of Dyneema rope [8] and two nichrome wire resistive heating elements as seen in Fig. 4. The Dyneema rope is made of ultra high molecular weight polyethylene (UHMWPE) fibres and connects the two clamp band halves.
UHMWPE experiences hardly no creep under tension and has a relatively low melting point of 140 °C, allowing it to be cut easily by a localised heat input. Two independent nichrome wires are connected to two independent control electronics to form the redundant actuation of the system. The wires make a one and a half turn spiral around the rope.
Alternatively, a Vectran fibre could also be used instead of the Dyneema. This material has very similar mechanical properties but a higher melting point of 500 °C, which makes it slightly more stable with even less creep. However, Dyneema was chosen due to its easier supply.

Tensioning bolt (5)

The tensioning bolt connects the two clamp band halves on the opposite site of the release system. The bolt-head support and nut are cylindrical as on Fig. 3. This allows the bolt to align itself with the clamp band as it is put under tension.
A correlation between applied torque and tension in the clamp band allows the tensioning to the desired force. This correlation still needs to be further calibrated using strain gauges on the clamp band, which has not yet been performed.

Springs and guides (6)

Four steel compression springs, press-fitted on their respective spring guides, are used to initiate the separation momentum during ground tests. They are also used during flight but might not be necessary, since the larger drag on the rocket's fins will already pull the mechanism apart.
The stainless steel spring guides are screwed in the lower aluminium ring. They also feature a threaded hole in their top. During the assembly of the separation mechanism, temporary assembly bolts are screwed through the holes in the upper ring, into the spring guides. This allows the upper and lower rings to be aligned and held in place with the springs compressed during the assembly of the clamp band. The separation mechanism can not be coupled to the next rocket module when these bolts are in place due to a mechanical interface, which rules out the risk of operator omission.
A cut of this feature is shown in Fig. 5, with the lower ring in dark blue, the upper ring in light blue, the spring in orange, the spring guide in yellow and the assembly bolt in red.

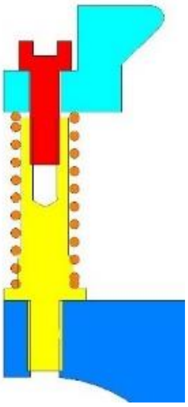

Figure 5. Temporary assembly bolt maintaining the spring compressed and rings aligned during assembly.

Aero-covers (7)

Four rolled aluminium sheet aero-covers are used to close off and protect the separation mechanism once it is fully assembled. The outer diameter of the closed assembly is identical to the rocket's outer diameter for aerodynamic reasons. The aero-covers also capture the clamp band once it has been released. Additionally, on the side of the tensioning bolt, the clamp band is secured to the rocket with a small rope pinched under the adjacent aero-cover.

STRUCTURAL ANALYSIS

The structural integrity of the separation mechanism under the loads specified in Tab. 2 was performed in two steps. Analytical calculations of the forces in the clamp band and contact pressures between each clamp and the rings where performed first. Finite element (FE) simulations where then conducted on the clamps, upper, and lower rings separately, using the load case (contact pressures) computed previously. The results and respective margin of safety (MoS) with respect to the material's elastic limit are given in Tab. 3. The maximum stress includes the factor of safety of 2 on the load. The resistance of the Dyneema rope is assumed to be 25 % of its breaking strength (see section on Dyneema loop tensile tests).
These calculations also showed that a tension of 750 N in the clamp band is sufficient to ensure no movement in the mechanism for any of the external loads.

Table 3. Structural analysis results

Part	Method	Max. stress	MoS
Clamps	FE	157 MPa	1
Lower ring	FE	200 MPa	0.25
Upper ring	FE	200 MPa	0.25
Spring steel band	Analytic	300 MPa	3.3
Dyneema rope	Analytic	375 N	0.3
Tensioning bolt	Analytic	220 MPa	4
Rivet hole bearing pressure	Analytic	240 MPa	4.4
Rivet shear	Analytic	375 N	3.75

As mentioned before, the critical load is due to the bending moment on the mechanism because the forces are not spread equally on all the clamps in that case. This load is easily simulated on the ground with the "spaghetti test" using the fully assembled rocket in flight configuration. The separation mechanism withstood the test without any problems.

ROPE CUTTING TIME

A simplified version of the thermo-electrical heat transfer model presented in [9], based on radiative and convective heat transfer, was used to characterize the nichrome heating. This numerical model was used to compute the optimal current through a 32 AWG nichrome wire, to obtain the fastest heating without damaging the wire (fusion around 1600 °C). The temperature evolution curve is shown in Fig. 6, where L is the length of the wire, D its diameter, R_w its resistivity, R_{ext} is the external resistivity of the circuit, V_{bat} the voltage applied on the entire circuit, I the current, and T_{max} is the highest temperature reached after 2 seconds of heating.
This model was validated by performing several proof of concept test of nichrome wire heating, with and without cutting of the Dyneema rope under various tensions. For all the tests with the Dyneema rope, the cut successfully happened between 0.7 s and 1.3 s.

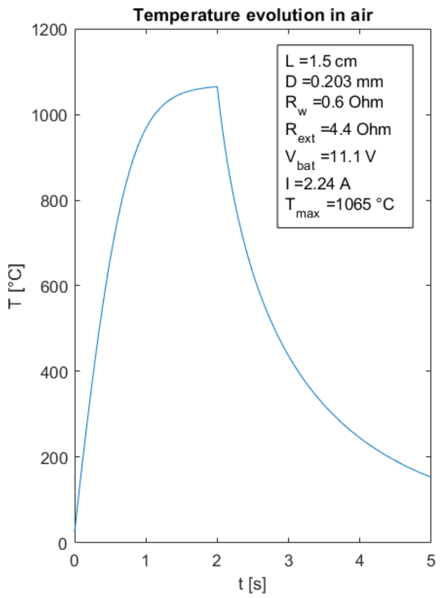

Figure 6. Nichrome wire temperature evolution in air.

DYNEEMA LOOP TENSILE TESTS

Due to its low friction coefficient, knots in UHMWPE are usually not very strong and start slipping at relatively low tensile forces. The tensile strength of the 1 mm SK78 Dyneema rope itself is 1950 N [8]. However, the maximum tensile force on a loop with a knot observed during tensile tests was between 400 and 1200 N (instead of 3900 N for a perfect loop).

Multiple knots were tested and the best results were obtained using a triple fisherman's knot, sealed with a special polyethylene cyanoacrylate super-glue and activator. In the 15 tests with this configuration, the knot started to slip between 1100 and 1450 N. Once the knot starts slipping, its resistance does not decrease and fluctuation of ±10 % around the initial slipping force are observed.
This resistance is sufficient for the minimum tension in the clamp band of 750 N, and justifies the assumed resistance of 25 % of the breaking strength used to compute the margin of safety (Tab. 3). Moreover, since the correlation between the applied torque on the tensioning bolt and the clamp band tension is not fully characterized, the onset of knot slipping is used to determine when sufficient tension is reached. This method induces a stronger tension than the required one, but it is not a problem since all the MoS on the other clamp band parts which are under tension are of 3.3 or larger.

SEPARATION TESTS

Nine separation tests in various configurations have been performed up to this date, most of them with the complete flight recovery electronics. Five tests were done with the uncoupled separation mechanism in different orientations. Three horizontal tests with cantilever mounted weights on the coupler interface, inducing a bending moment of up to 50 Nm, were also conducted. Finally, a "static" separation test with slow release of the four temporary assembly bolts after cutting of the Dyneema loop was performed to study the role of the dynamics during the separation. All nine ground separation tests were successful.

CONCLUSIONS

A new separation mechanism for high-power model rockets has successfully been developed and tested on the ground. It will enable the Bella Lui II rocket, and the ERT's future rockets, to separate reliably at apogee and deploy their recovery parachutes. The separation mechanism's structural strength allows it to be placed lower on the rocket and enables a more symmetric separation. It is a structural part of the rocket during ground handling and ascending flight. The design is based on a clamp band system which can be opened by a novel Dyneema burn wire release system, and does not require any pyrotechnic actuation.
The structural integrity of the assembly was validated by analytical calculations and finite element methods with a safety factor of 2 on all external loads. The smallest safety margin is found on the upper and lower aluminium ring for the bending load case due to radial acceleration, and is equal to 0.25.
The tension in the clamp band is limited to ~1000 N due to the knot of the Dyneema loop starting to slip. This value is larger than the required 750 N of tension, and

ensures no movements of the parts in the mechanism for any of the load cases. Tensile tests have also shown that no reduction of strength is observed once the knot starts slipping.

The Bella Lui II rocket with the new separation mechanism is scheduled to fly for the first time at the end of July of 2021 in Wasserfallen, Switzerland. The EPFL Rocket Team also participated in the virtual SAC in June of 2021 with this rocket, and won several awards such as the second place in its category, as well as a second place in the Dr. Gil Moore award for innovation for the new separation mechanism. The team will also participate in the EuRoC in Portugal, where they will launch the rocket for the second time.

With the experience of building this first iteration of the separation mechanism, several optimization ideas have also been identified. Simplifications of the clamp band would mainly allow a reduction of the number of parts and their complexity. Moreover, if the clamp band and its interfaces can be made smooth enough, the mechanism would no longer require any aero-covers and the clamp band's outer diameter could be equal to the airframe diameter. This would reduce the risk of a potential failure, where the clamp band interferes with the aluminium rings during the separation, as well as increase the free inner diameter for parachute passage.

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