Individual Analysis Report

Team 4 – Team Stellar Hold

Sponsored by General Atomics – EMS
Hold Down Release Mechanism

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1. Introduction

The purpose of this analysis is to determine the forces that the locking mechanism experience when loaded and when being unloaded. This design utilizes a concept of locking ball bearings into a location that prevents motion from the pin, which is the main function. The lock is held in place via a bias spring, and then moved out of place with the use of a shape memory alloy (SMA) spring that expands when heated. There are many factors that may have an effect on these forces, such as the angle of contact with the ball, the size of the ball, the materials involved in contact, and the force of the bias spring that holds the lock in place. This analysis ultimately leads to an evaluation of the minimum force that the SMA spring needs to exert to push the lock and reliably open the device.

Microsoft Excel was used for these calculations as many of the geometries for the final product are either unknown or likely to change. This includes the properties of the COTS springs that will be used as bias springs. By constructing a comprehensive spreadsheet, it serves as an analysis tool for future calculations of this subsystem as well as an initial analysis with reasonable assumptions.

The remainder of this document will outline the systems being analyzed for forces, define the relevant variables, and introduce the spreadsheet analysis tool that is developed for this combination of systems.

2. System Definition

2.1. Main System

Figure 1 shows a cross-section of the device, with annotations displaying the dynamic systems being analyzed. System A shows the ball bearings, which experience a force imposed by the piece in between both bearings. System B focuses on the piece surrounding the central shaft, extending to either side and upwards to make contact with the ball bearing. Figures 2 and 3 give more detailed sketches of the forces being exerted on systems A and B.

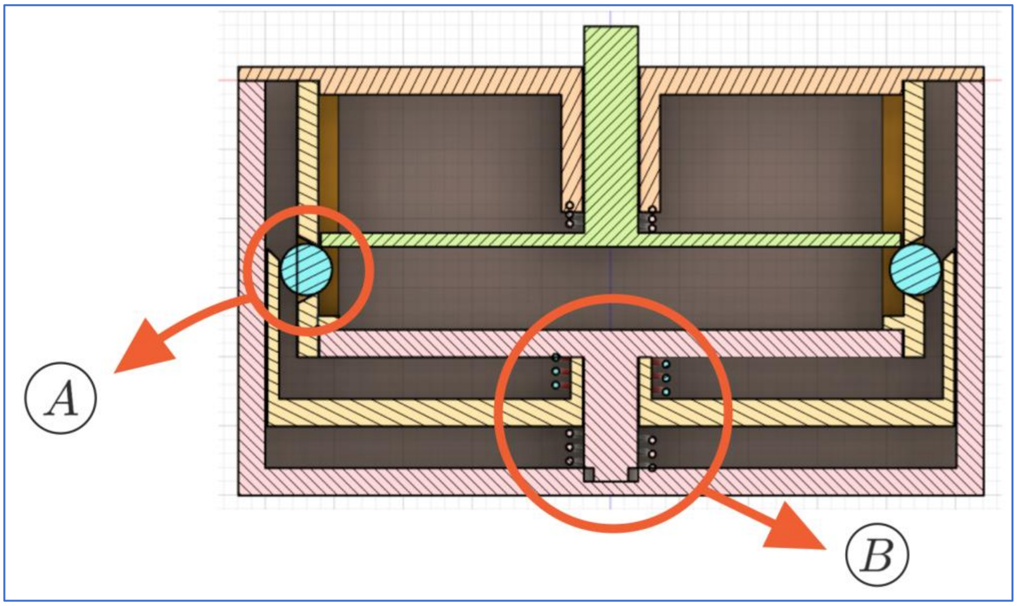

Figure 1: Cross-section of device, annotated to show the two systems being analyzed.

2.2. Subsystem A

Subsystem A, as shown in Figure 1, will be an analysis of the ball bearing interacting with the forces from the pin and the wall of the lock, which is a part of subsystem B. Figure 2 outlines the forces that are relevant for this system. The bearing sees a center-offset vertical force imposed by the pin, which induces a horizontal force that is delivered to the wall of the lock. This horizonal force is normal to the surface of the lock, which imposes a friction force when the lock attempts to slide. The remainder of the forces on the lock are shown in section 2.3. See section 2.4 for variable definitions.

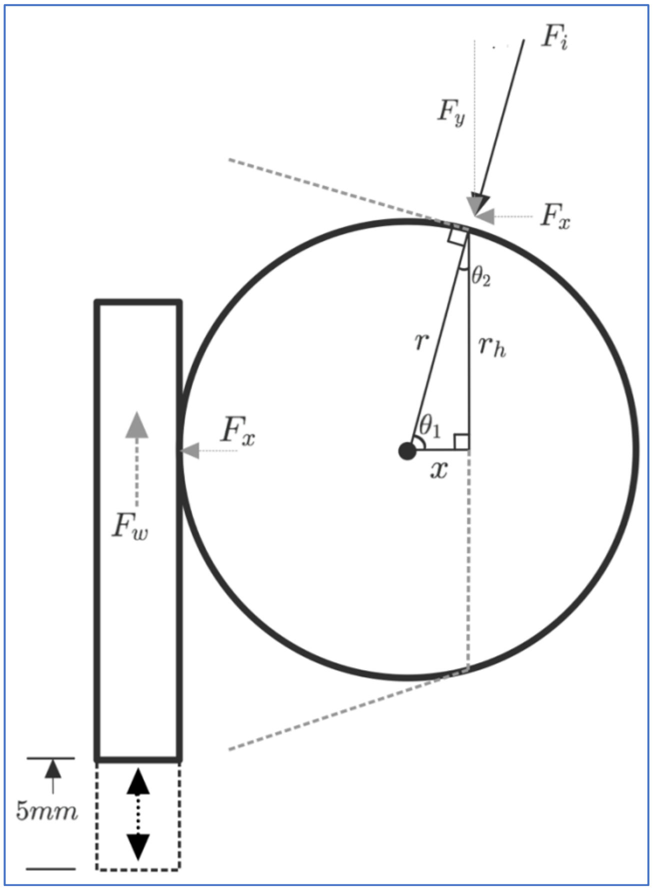

Figure 2: Diagram of subsystem A containing the ball bearing interacting with the forces from the pin and the wall of the lock.

2.3. Subsystem B

Subsystem B, as shown in figure 1, looks at the lock interacting with the friction forces from both ball bearings and the force from the bias spring. The friction forces are scaled by an assumed factor of safety, and ultimately used to determine the specifications of the bias spring and the SMA spring. Figure 3 displays a diagram of these forces on this component.

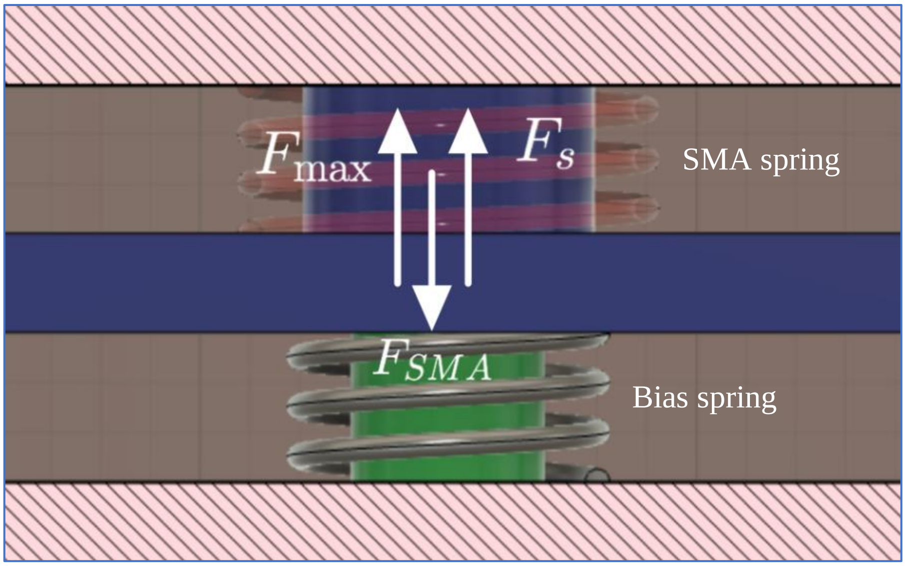

Figure 3: Diagram of forces on subsystem B, showing frictional forces, spring forces and force of SMA spring.

2.4. Variable Definitions

Tables 1 and 2 outline and defines the variables that are relevant to these analyses, including the variables names shown in the previous figures and variables used in intermediate calculations and equations. Table 1 and 2 includes definitions relevant to subsystem A and B, respectively.

Table 1: Variable definitions for subsystem A

Variable	**Definition**
θ_1	Angle of attack from horizontal
θ_2	90º minus θ_1
F_y	The amount of vertical force exerted on each bearing
F	Friction factor assumed between bearing and wall
D	Diameter of bearing
R	radius of bearing
SF_1	Factor of safety/scale factor for wall friction
X	x-distance from F_y and bearing center
r-x	length of bearing protruding from hole
r_h	radius of bearing hole
D_h	Diameter of bearing hole
F_i	Total force on bearing
F_x	Horizontal force on bearing
F_w	Friction force from bearing onto wall
F_s	Amount of force to move wall lock down

Table 2: Variable definitions for subsystem B

Travel	Assumed range of motion for locking mechanism
L	Length of spring
k	Spring constant
Fcomp	Spring force at maximum compression
xcomp	Spring length at maximum compression
C	Constant allowing for cut-in force
stroke	full range of motion of spring
SF2	Factor of Safety for bias spring
Fmin	Friction force for both bearings times SF2, to overcome friction force
Xmin	minimum compression for spring to achieve minimum force
Lmin	length of spring @ min compression
Xmax	Maximum compression of spring based on travel distance
Fmax	force exerted by spring at max compression
Lmax	length of spring @ max compression
Fsma	Minimum force required for SMA spring

3. Analysis & Spreadsheet

This section will introduce the spreadsheet used and the equations driving some of the calculations. Table 2 displays the calculations for subsystem A, the ball bearings. The cells that are highlighted in orange are input cells, and yellow and green denote important values. Some input values are assumed, such as theta, D, and the safety factors. Others are taken from online sources (friction factor [1]) or the engineering requirements. Refer to the previous figures and tables for variable definitions and diagrams.

3.1. Subsystem A

The goal of this part of the analysis is to evaluate and provide a tool to relate contact angle with the ball to the amount of friction between the ball and the lock wall. The results proved that as θ_1 increases to a maximum of 90º, the friction force decreases to zero. However, the mechanism requires that there is some horizontal component due to the fact that the pin exerting the force on the bearing must also move it to the side.

Additional effects of increasing θ_1 are

- decreasing the horizontal distance between the vertical force and the center of the bearing
    - decreases friction force
- increasing the diameter of the hole the bearing sits in
    - makes manufacturing tolerances more difficult
- increasing the length of the bearing that protrudes from the hole.
    - Provides a sturdier surface to block the motion of the pin

By increasing the diameter of the hole the bearing sits in, it reduces the friction forces, but may be more difficult to manufacture with proper tolerances. Therefore, an angle of 70º was chosen to balance out these trade-offs. As F_y is known, F_w, the friction force on each wall is calculated from equation 1. The remainder of the values are calculated using simple trigonometric relationships, knowing the radius, angle, and F_y.

$$F_w = f \times [F_y tan(\theta_2)] \quad (1)$$

A friction factor was found for steel-steel contact, with dry and clean conditions to be 0.5. This may be reduced by using lubricants that are safe to be deployed in space, however 0.5 is likely an upper bound of the friction factor to assume the highest friction forces. A ball bearing diameter of 3mm is assumed, however changing the diameter does not affect the forces, as long as the angle of the force remains the same. Finally, a safety factor for the friction force was assumed to be 5, so the system must provide 5x the frictional force when counteracting it. Resulting from this section, F_s is the frictional force from two bearings, times the safety factor. This represents the amount of force required for the SMA spring to push past the friction.

Table 2: Analysis results for Subsystem A, ball bearing

Bearing Dimension Analysis			
ASSUMPTIONS / GIVEN			
Variable	Value		Units
theta1	70	1.22	[deg] [rad]
theta2	20	0.35	[deg] [rad]
Fy	12.5		[N]
f	0.5		[-]
D	3	0.003	[mm] [m]
r	1.5	0.0015	[mm] [m]
SF1	5		[-]
CALCULATIONS			
	Value		Units
x	0.51		[mm]
r-x	0.99		[mm]
Dh	2.82		[mm]
Fi	13.30		[N]
Fx	4.55		[N]
Fw	2.27		[N]
Fs	22.75		[N]

3.2. Subsystem B

The analysis of subsystem B serves to provide forces and geometric information that aids in the selection of springs. This section uses forces calculated above (F_s and F_w highlighted in yellow) as criteria for if a spring can work with the system modeled by these assumptions. The input cell for the Travel variable is assumed, representing the full range of linear motion of the lock (subsystem B). The remainder of the input cell values are taken from spring data and tested for fitness.

The F_{min} value is calculated from SF_2, which is assumed to be 2, and the friction force F_w, calculated in table 2. This is used so that regardless of the springs position, it will always be able to push the lock back into locked position regardless of the friction force. This is modeled by equation 2.

$$F_{min} = 2 \times F_w \times SF_2 \tag{2}$$

The displacement of the selected spring required for that force is calculated, and then based on the prescribed travel length, 5mm, the maximum force and compressed spring length are calculated after being compressed.

The criteria for success are

- The selected spring must be able to compress at least the travel length.
- The spring must be able to obtain both the minimum and maximum force calculated while remaining within its range of motion.
    - Explained differently, by compressing the spring to the minimum force prescribed and then compressing it 5mm further, the resulting spring length cannot be shorter than the minimum length of the spring.

These two values are highlighted in green in table 3 to show that it meets the criteria; if it failed it would highlight red. In addition to meeting the force and travel requirements, another aim of this analysis is to minimize the uncompressed spring length. That value is highlighted in yellow in table 3. While this value varies per spring, all of the springs analyzed remained withing the 13-15mm range. The force and displacement values are determined by manipulation of equation 3, and values previously defined in the sheet.

$$F = k(x) + C \tag{3}$$

Finally, assuming a compatible spring has been selected, the minimum force for the SMA spring can be calculated. Observing figure 3, equation 4 can be derived from a force balance. This minimum force for the SMA spring takes into account the frictional force on the wall and the counterforce from the bias spring, both accounting for their safety factors. The selected spring is from McMaster[2].

$$F_{SMA} = F_{max} + F_s \tag{4}$$

Table 3: Analysis result from subsystem B, springs.

Bias Spring Analysis			
Spring Used:	2022N173		from McMaster
Variable	Value		Units
Travel	0.20	5.00	[mm]
L	0.62	15.75	[in] [mm]
k	27.50	4.82	[lbs/in] [N/mm]
Fcomp	8.13	36.16	[lb] [N]
Xcomp	0.32	8.13	[in] [mm]
C	-0.12	-0.53	[lb] [N]
Stroke	0.30	7.62	[in] [mm]
SF2	2.00		
Fmin	2.05	9.10	[lb] [N]
xmin	0.08	2.00	[in] [mm]
Lmin	0.54	13.75	[in] [mm]
Xmax	0.28	7.00	[in] [mm]
Fmax	7.46	33.18	[lb] [N]
Lmax	0.34	8.75	[in] [mm]
Fsma	12.57	55.93	[lb] [N]

4. Conclusion

The results of this analysis confirm the fact that as the angle of contact between the pin and the ball bearing decrease, in this case becoming more horizontal, the minimum force required for the SMA spring increases greatly. Therefore, more research needs to be conducted as for how precise the diameter of a small hole can be machined. This will determine how steep the contact angle can be, minimizing the force required for the SMA spring. At 70º vertical contact between the pin and the ball bearings, with the selected spring, the minimum required SMA force is near 56N, or 12.6lb.

Moving forward, this excel sheet will serve to analyze different combinations of geometry for the ball bearing, springs, and material to meet the engineering requirements while minimizing the force requirements for the device.

5. References

[1] "Friction - Friction Coefficients and Calculator." https://www.engineeringtoolbox.com/friction-coefficients-d_778.html (accessed Apr. 20, 2022).

[2] "McMaster-Carr Mil. Spec. Compression Springs." https://www.mcmaster.com/2022N173 (accessed Apr. 20, 2022).