Design to replace electric motors with mechanical springs in a climbstation

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ABSTRACT

Joyride Games Oy wanted to explore the possibility to use mechanical springs as a replacement to electric motor currently driving their device i.e. a climbstation. I was commissioned to do a research and development work for this case as my Bachelor's Thesis by Kaarle Vanamo (CEO of Joyride Games Oy). In a situation where the use of electric motors in machines are extremely high because of their reliability and efficiency, the commissioner wanted to find out what chances would mechanical springs carry in this specific application? To check this, I proposed some design ideas and for one most potential idea I have developed a mechanism and presented its analysis results in this thesis.

This project started with background research and brainstorming followed by kinematic modeling, static calculations, making of a 3D CAD model, performing a force analysis in Creo Parametric, running finite-element analysis simulation in ANSYS Workbench and ended in comparing the results. Results of the analysis indicate that the mechanism was capable of performing the required function. However, the mechanism is not yet capable of handling a total load of 30 KN.

This thesis can be a helpful reference for upcoming research and design works on this topic.

Keywords Mechanism, spring, cam, climbstation

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1 INTRODUCTION

Climbstation is the device used for indoor climbing manufactured by Joyride Games Oy. It is a mechanical device driven by an electric motor. The electric motor can perform a frequent changes of direction by receiving an input signal. The downside of an electric motor is its high cost which in turn increases the cost of climbstation. The company wants to reduce the cost of climbstation by replacing currently used electric motors with a combination of mechanical springs and a linear engine. This thesis was commissioned by Joyride Games Oy as a development project to replace electric motors with mechanical springs.

Motors are used to produce linear or rotatory force in most of the industrial and household electric devices. They are efficient, easy to install and use. Moreover, they are easily available in the market with various specifications and applications. On the other hand, mechanical springs or wire springs are elastic objects that are designed for compression and tension, whose function is to store mechanical energy. There are heavy duty springs which are capable of handling a large amount of forces. Mechanisms that require a great amount of force use this kind of springs. With that said, the possibility of using mechanical springs as an alternative to electric motors is an unexplored topic.

I have taken a solution-based approach in this case. Although my results might not be accurate as to the initial goal, the ideas, the design process and the solutions presented here can be a source of reference to anyone who will be working on similar tasks.

2 CLIMBSTATION BACKGROUND

A climbstation is a device for indoor climbing. This is an alternative method for rock climbing and wall climbing. Joyride Games Oy design and manufacture climbstations. Climbstations are mainly used for the physical workout and used in gyms. It is also taken as a sport and used in game hubs and shopping malls. A climbstation only requires 200 cm× 400 cm of floor space and easily fits in a room. It requires no safety harness, ropes or instructors.

The technical aspects of a climbstation involve: mechanical frames, a conveyor, hydraulic cylinders, electric motors, sensors and other miscellaneous components. The current climbstation is an automated device. This device stands on the support of its base. It also has a wall on a standing position. The wall rotates and can be positioned between +15° and -45° for climbing. The force required to rotate the wall is 20-40 kN. This force is generated by an electric motor and transferred to the wall by hydraulic cylinders. The outlook of climbstation can be seen in Figure 1.

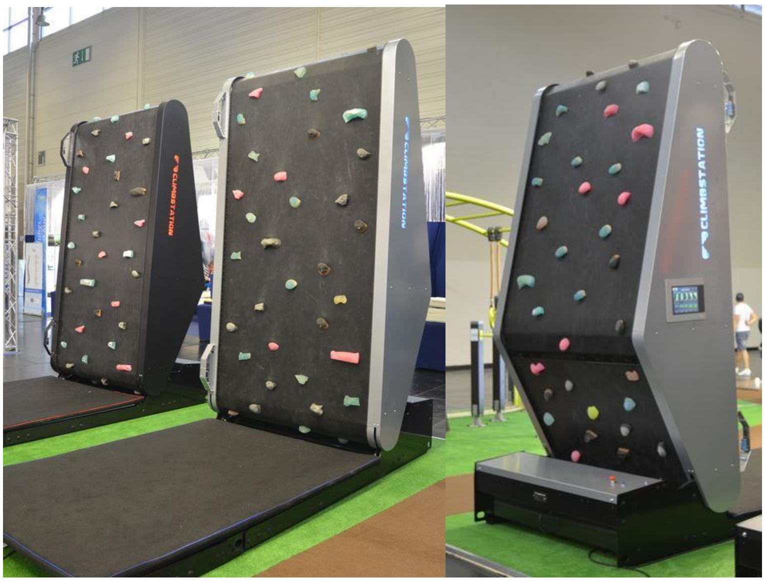

Figure 1. Front and back view of climbstation (Joyride Games Oy n.d.).

3 DESIGN SPECIFICATIONS

Now, in this case, the task was to explore the possibility of replacing the electric motor with mechanical springs and a linear engine. The linear engine was capable of producing the force of 6-10 kN. Remaining 14-30 kN force was preloaded on mechanical springs. These mechanical springs were later loaded by the force generated by gravity acting on the wall. This thesis explored different ways of using the springs and transferring force between the springs and the wall.

A climbstation must be able to perform all the functions that it was performing. It could be programmed to tilt according to the requirement of the climber. It had a user interface in which commands could be input. With an electric motor, this could be achieved easily. But with springs, it could be a huge challenge. This thesis tried to explore the possibilities to overcome those challenges. A list of requirements is given below:

- Rotate the wall as current Climbstation
- Withstand the forces
- Do not consume more floor are than current Climbstation
- Allow Climbstation to be modified for future upgrade
- Response as quickly as current Climbstation

4 SCOPE OF DESIGN

My responsibilities were to explore the possibilities of replacing the electric motor with mechanical springs. The company had already purchased the springs. They also had developed the initial idea of placing the springs and using a linear engine to assist the springs. I had to provide possible ways, design and develop a system, analyse it and if possible build a working prototype. Below are the information provided initially by the company.

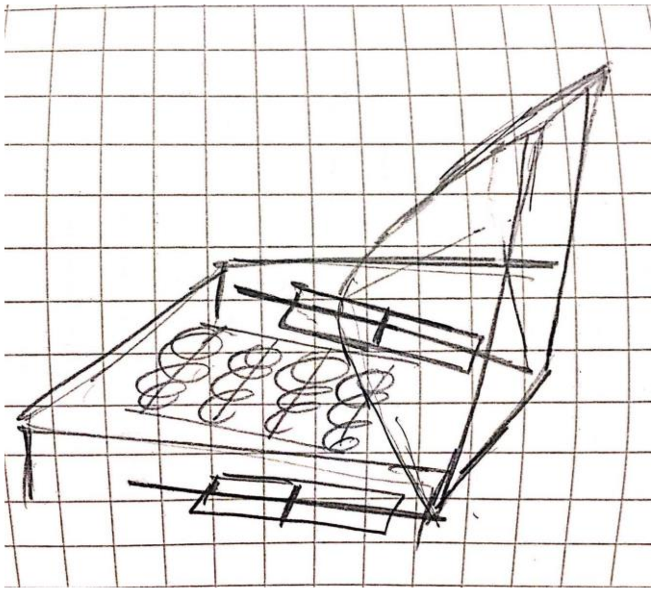

Figure 2. Sketch of idea about placement of springs.

As shown in Figure 2, a spring and a piston-rod move at 2 different axes. Because of this, the main concern was to transmit piston force which is in one axis to the springs which are in different axes.

5 THEORY

5.1 Spring

Springs are flexible devices used to store elastic energy and when required release stored energy in the form of force or torque. Spring produces the force which can be compressive or tensile and linear or radial. A certain force is used to deflect the spring. While a spring is being deflected, energy is transferred into stored spring energy. Stored spring energy will be returned when the force causing the spring deflection is removed. Nature and direction of force or torque exerted by springs when they are deflected classifies the springs. Although any material can be used to make springs, the material having a high ultimate strength and yield point and a low modulus of elasticity is able to provide maximum energy storage and are ideal to be chosen. (Yamane, Childs, Obikawa, & Maekawa 2003, 225.)

Helical compression springs are the type of springs which have constant diameter round wire and constant pitch (Yamane, Childs, Obikawa, & Maekawa 2003, 229). A helical spring is shown in the Figure 3:

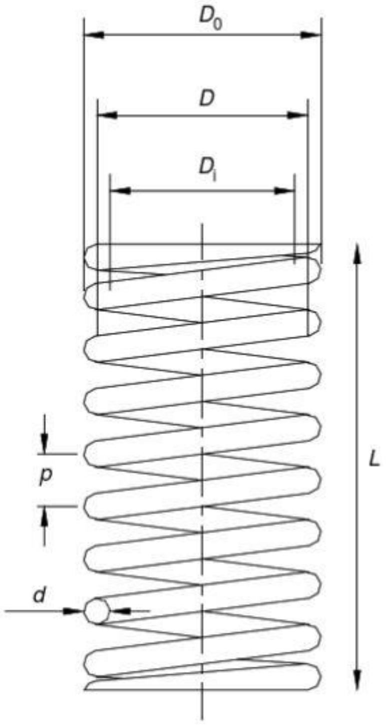

Figure 3. Dimensional parameters for helical compression springs (Yamane, Childs, Obikawa & Maekawa 2003, 230).

In Figure 3:
D_o is the outside diameter of the spring
D_i is the inside diameter of the spring
D is the mean diameter of the spring
d is the diameter of the wire
p is the pitch of the spring
L is the free length of the spring

5.2 **Kinematics and mechanisms**

Kinematics is a branch of dynamics which studies the way bodies move. Kinematics can also be described as the study of the geometry of motion. Kinematic analysis can be applied in the design of mechanisms involving gears, cams, linkages and other parts. It helps to produce desired motions by determining position, displacement, rotation, speed, velocity and acceleration of a mechanism.

A mechanism is the mechanical portion of a machine that has the function of transferring motion and forces from a power source to an output (Myszka 2012, 1). A mechanism can be considered rigid parts that are arranged and connected so that they produce the desired motion of the machine (Myszka 2012, 2).

A mechanism is an arrangement of parts in a mechanical device or machine. Linkages are used in this design. Mechanisms play an important role in daily activities. Every modern convenience from the toaster used to make part of your breakfast to the automobile that you drive to school or work is made up of one or more mechanisms.

When we look around us, we can see that we are surrounded by machines and mechanisms. There are several applications of mechanisms. They can be found in robots used for picking and placing, walking and exploratory robots, transmission, clutch and shifter of automotive devices. Heavy equipment like amusement park rides, garbage truck lifting, compacting, and dumping, farm equipment like harvester, thrasher etc. are examples of mechanisms. Other application areas involve consumer electronics, home appliances, furniture, office equipment, sports equipment, tools, and toys.

5.3 Mechanism terminology

a) Frame

One part is designated the frame because it serves as the frame of reference for the motion of all other parts (Myszka 2012, 2).

b) Link

Links are the individual parts of the mechanism. They are considered rigid bodies and are connected with other links to transmit motion and forces (Myszka 2012, 2).

c) Joint

A joint is a movable connection between links and allows relative motion between the links. There are two types of joints: primary and higher order. The primary joint allows either a pure rotation or pure sliding. On the other hand higher-order joint allows both rotation and sliding. (Myszka 2012, 2.)

d) Degree of freedom

The degree of freedom is the number of independent inputs required to precisely position all links of the mechanism with respect to the ground (Myszka 2012, 2).

Degrees of freedom for planar linkages joined with common joints can be calculated through Gruebler’s equation (Myszka 2012, 2.):

$$M = \text{degrees of freedom} = 3(n-1) - 2j_p - j_h \quad (1)$$

Where:

n = total number of links in the mechanism

j_p = total number of primary joints(pins or sliding joints)

j_h = total number of higher-order joints (cam or gear joints)

e) Point of interest

A point of interest is a point on a link where the motion is of special interest (Myszka 2012, 2).

6 DESIGN PROCESS

The design process is a continuous process in product development from the discovery of the problem or needs to a completed hardware that solves the problem or meets the need. It is a set of rules and guidelines which help to lead a designer to a direction but it doesn't provide any guarantee of success. It helps engineers to make decisions, analyse them and make certain changes if required. A design of anything is done either to solve a certain problem, fulfill needs or to generate an application of available resources. From start to the final product of a design, the process is subjected to analysis, evaluation, refinement and development.

In this case, the design process was as illustrated in Figure 4:

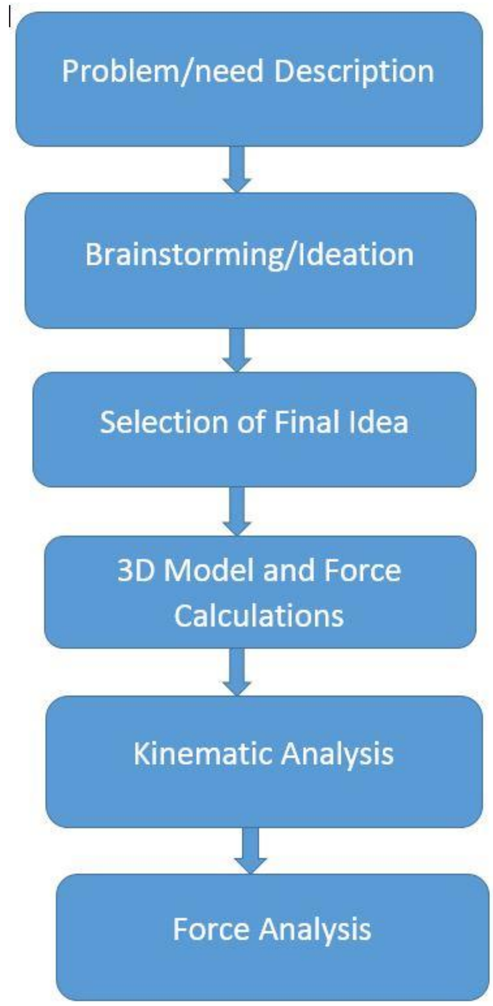

Figure 4. Block diagram of Design Process.

The design process started with the determination of the appropriate movement of the wall. A mechanism was designed to achieve the desired movement of the wall. This mechanism involved certain components, whose individual motion and overall motion of mechanism should be analysed. Also the effect of force acting in the mechanism should be analysed.

7 SOFTWARE

Three essential software programs used in mechanical engineering were used in this thesis. They were used for calculations, for creating a digital prototype (3D model) and for performing the force and strength analysis.

7.1 Creo Parametric 2.0

Creo parametric 2.0 is a 3D CAD software for product design produced by PTC. In this thesis, a 3D model of climbstation was created with Creo Parametric 2.0. Each component was separately created. After that, all the components were assembled. The components could perform the movement required in this project.

Figure 5. Creo Parametric 2.0.

7.2 Mathcad

Mathcad is an engineering math software produced by PTC which can be used to perform, analyse and share mathematical calculations. In this case, Mathcad was used to calculate the unknown values and conduct an analysis of the mechanism.

7.3 ANSYS Workbench 17.2

ANSYS workbench platform is an engineering software which can perform very complicated analyses during a design process. The ANSYS workbench was used here for the analysis of engineering issues related to structural, mechanical, flow, electromagnetic etc. The ANSYS workbench can be used to find the responses of bodies (solid, surface, or line bodies) also known as problem domain, subjected to different environmental conditions (loads and supports). The ANSYS workbench provides results such as displacements, stresses or strains of bodies.

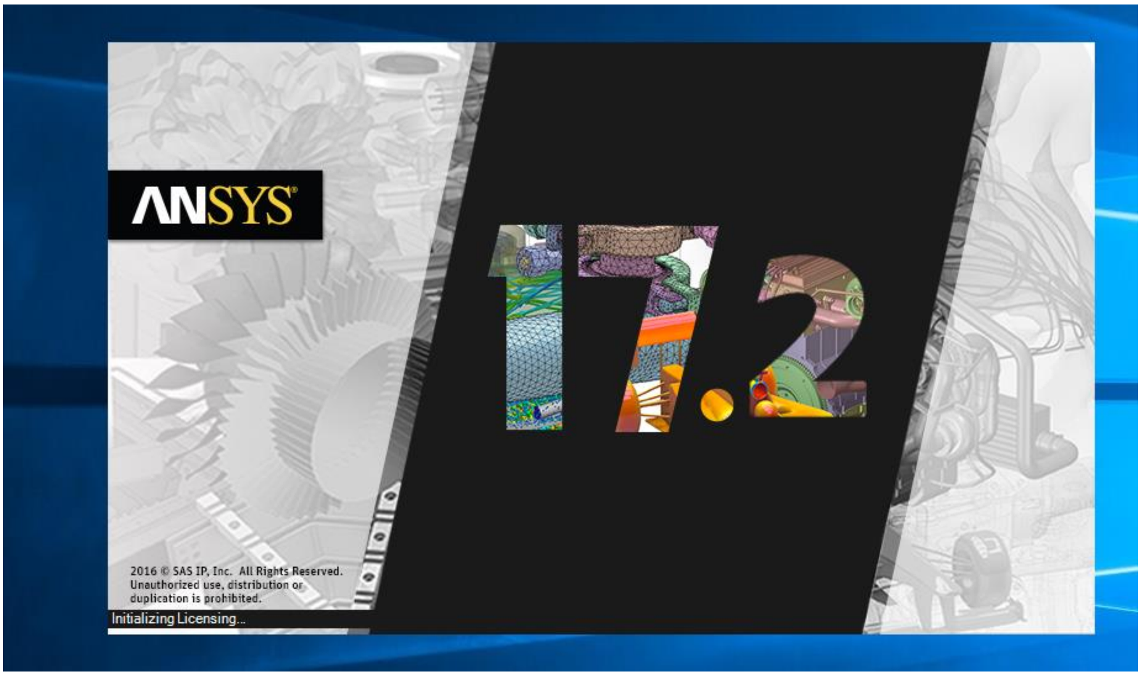

Figure 6. ANSYS Workbench 17.2.

The steps followed by ANSYS workbench for analysis are given below:

1. Setup Analysis Environment

This involves:

- Choosing type of Analysis
- Defining Engineering data

2. Build a model

This involves:

- Importing files
- Creating parts in Design Modeler

3. Apply Boundary conditions

This involves:

- Defining Connections
- Applying Mesh Controls
- Applying loads and supports

4. Solve
5. Review Results

In this case, 3D CAD model created in Creo was imported in ANSYS for further analysis.

8 DESIGN IDEAS

As mentioned earlier, the new design was to be equipped with compression springs and a linear motor. Therefore, design ideas had to involve a way to compress the springs and return the springs to their original shape. While compression and returning to original shape, springs must store and release force required to rotate the wall. In the early phase of this thesis, brainstorming sessions were conducted and ideas were generated.

Sketches of ideas are illustrated to understand how the mechanism looked like. The working principles are further explained here.

8.1 Idea 1

In this idea, a group of mechanical components are combined to form a mechanism. This mechanism squeezes itself and compresses the springs in the process. The covering plates and floor plates are considered as the frame.

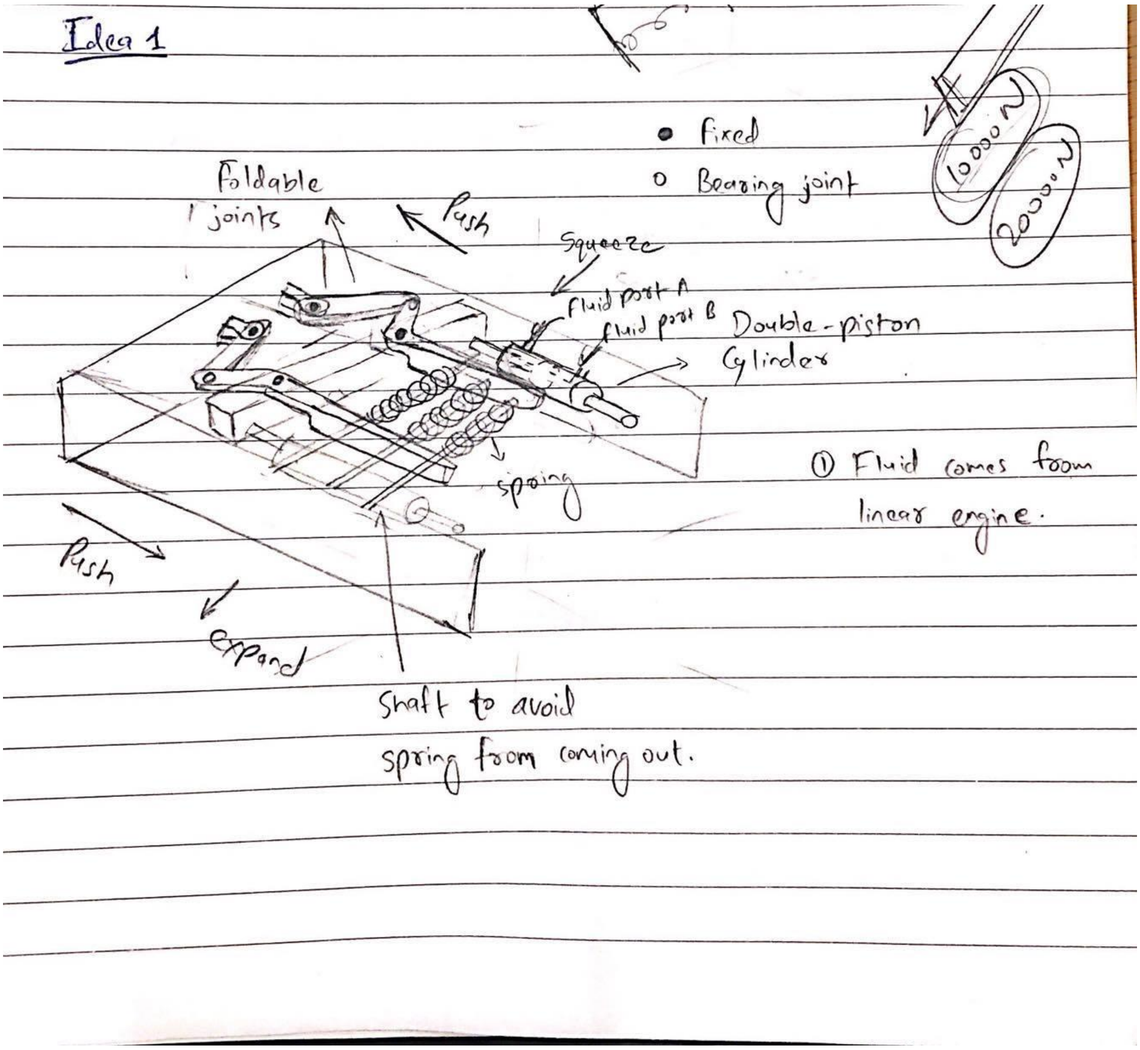

Figure 7. Sketch of idea 1.

There are five moving parts:

I. 2 connecting arms or lever arms
II. 2 Spring-wall
III. 1 Pushing shaft

Pushing shaft is connected to the cylinder rod, and hence moves in the same path as the cylinder rod. As the cylinder rod moves, it transmits the force from the wall. Spring-walls are connected to the pushing shaft with fixed joint. Spring-walls are also connected to the connecting arms with bearing joints. Lever arms are connected to the back plate with bearing joints. Therefore, when cylinder rod moves towards the direction of back plate, pushing shaft also moves in the same direction. Bearing joints enable connecting arms to rotate which results in a squeeze of the mechanism. This causes spring-walls to come closer to each other. Hence compressing the springs between them.

During the compression of springs, the climbing wall is tilting in the clock-wise direction. In this process, linear motor assist the mechanism by moving the fluids from port B towards port A which enables the movement of the piston rod.

Since both bars had same function, they were considered to be one single moving part. The same principle was applied with spring-wall. Overall 1 frame and 3 moving parts were established.

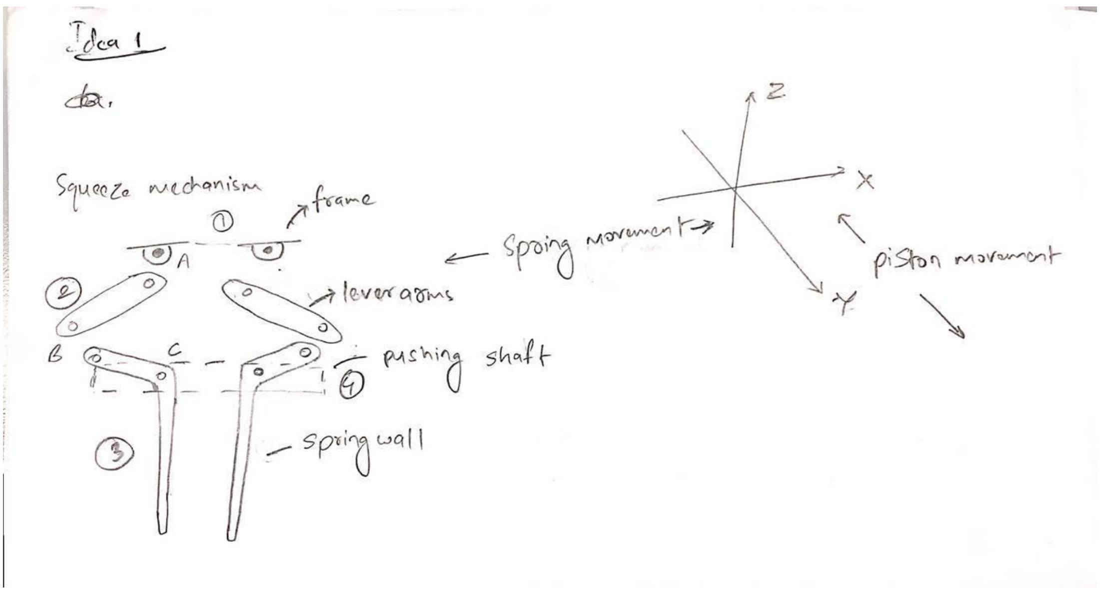

Figure 8. Sketch of components used in idea 1.

Frame:
Back wall acts as the frame. The frame is considered as link 1.

Other links:

Bar that connects frame and spring-wall is considered as link 2.
Spring-wall is considered as link 3.
Block connected to spring-wall is considered as link 4.

8.2 **Idea 2**

In this idea, three hydraulic cylinders are used as shown in Figure 9. Springs are placed around the piston. Single rod cylinders are used. Two parent hydraulic cylinders are present at two opposite sides. The view shown in Figure 9 is just one side of mechanism. One parent hydraulic cylinder is shown. The same principle applies to the other side.

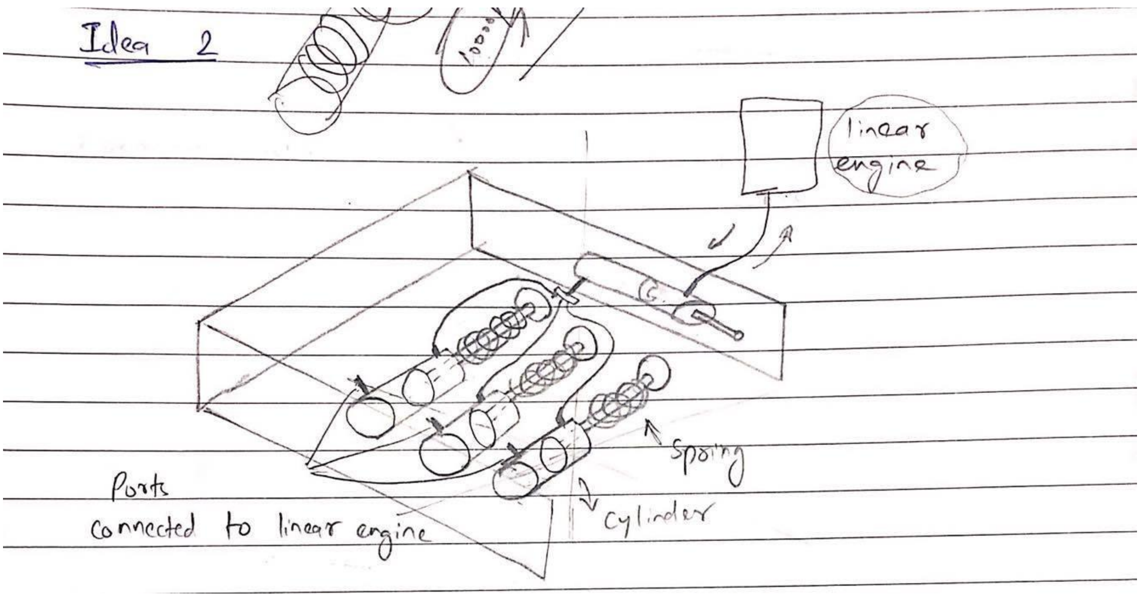

Figure 9. Sketch of idea 2.

The working principle of this mechanism is in steps as follows:

<u>Step 1</u>: The wall is in standing position. Linear motor releases the fluid, causing the piston to move. This rotates the wall in the clockwise direction. When wall rotates, piston-rod will move inside the main cylinder.

<u>Step 2</u>: Fluids coming out from main cylinder distributes and enter through input ports of 3 cylinders. Fig () shows a formula racing damper. This concept can be used as spring attached cylinder. This damper currently doesn't have an input and output ports for fluids.

Figure 10. Formula Racing Damper (ZF n.d.).

In Figure 11 there is a picture of a hydraulic cylinder. The spring can be placed around the rod of this kind of cylinder as shown in the damper in Figure 10.

Figure 11. Parker Hydraulic Cylinder (Parker n.d.).

Step 3: Entering fluid push the piston in one direction. As the pistons inside 3 cylinders move, springs are compressed. Springs store certain force. By the time, the wall is tilted to its maximum limit, springs are compressed to their maximum limit.

Step 4: To rotate the wall in an anti-clockwise direction, first linear motor push the fluid in opposite direction. This will start the movement of the piston and additional force is provided by the compressed springs as they tend to return to their original shape.
Finally, the wall will again come to the standing position as overall stored force is released.

8.3 **Idea 3**

In this idea, springs are placed between two movable plates (spring-wall). Cam is connected to one end of piston-rod as shown in Figure 12. Centre of the cam is connected to a stand and is able to rotate. When the wall is rotating in the clock-wise direction, piston and rod of the cylinder move towards back plate. This causes the cam to rotate. Cam is attached to the spring-wall with a frictionless joint. As the cam rotates, spring-wall is pushed. This working principle works from both sides. Hence, springs are compressed and force is stored in springs.

In order to rotate wall in an anti-clockwise direction, the linear engine will assist as mentioned in idea 1&2 and previously compressed springs will start to retain their original shape, releasing stored force. Therefore, transferring force to the wall.

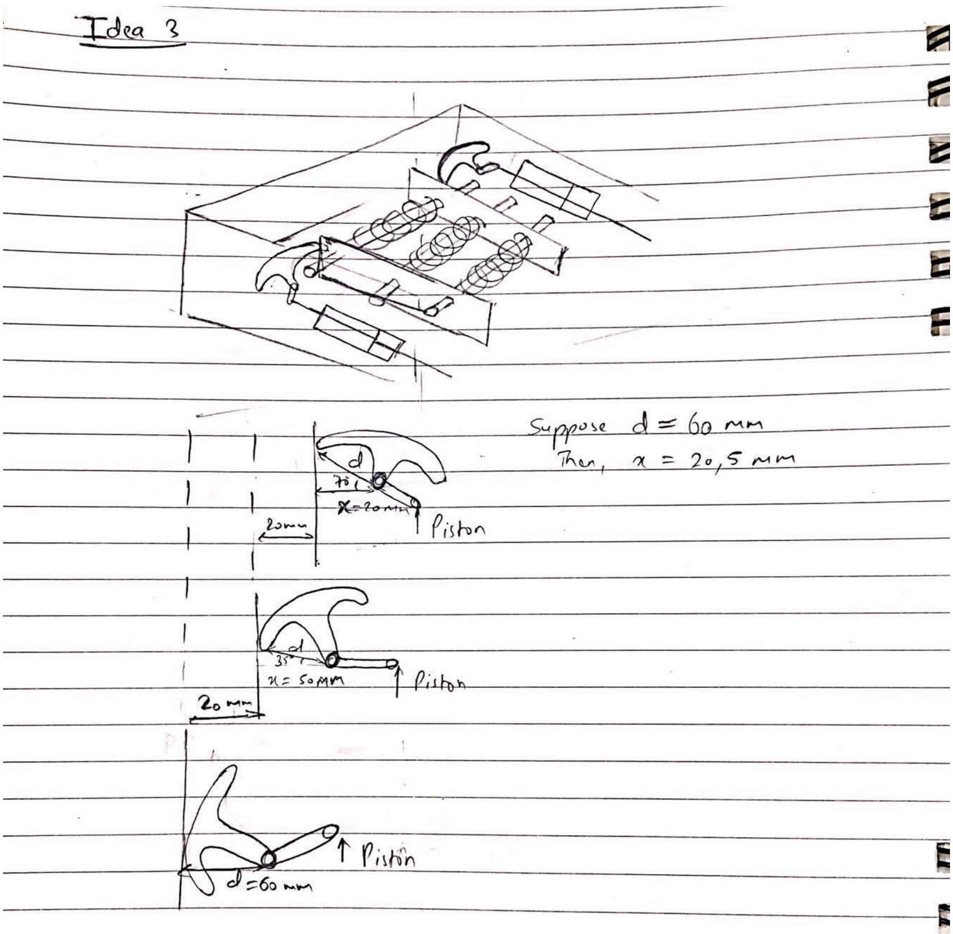

Figure 12. Sketch of idea 3.

8.4 **Idea 4**

In this idea, helical extension springs are used instead of compression springs. Rotating arm is used. Springs are connected to those arms as shown in Figure 13. When the wall is rotating in the clock-wise direction, piston-rod moves towards the back plate and moves one arm in the same direction so that springs are extended. Force is stored in springs.

In order to rotate wall in an anti-clockwise direction, the linear engine will assist as mentioned in idea 1&2 and previously extended springs will start to retain their original shape, releasing stored force. Therefore, transferring force to the wall.

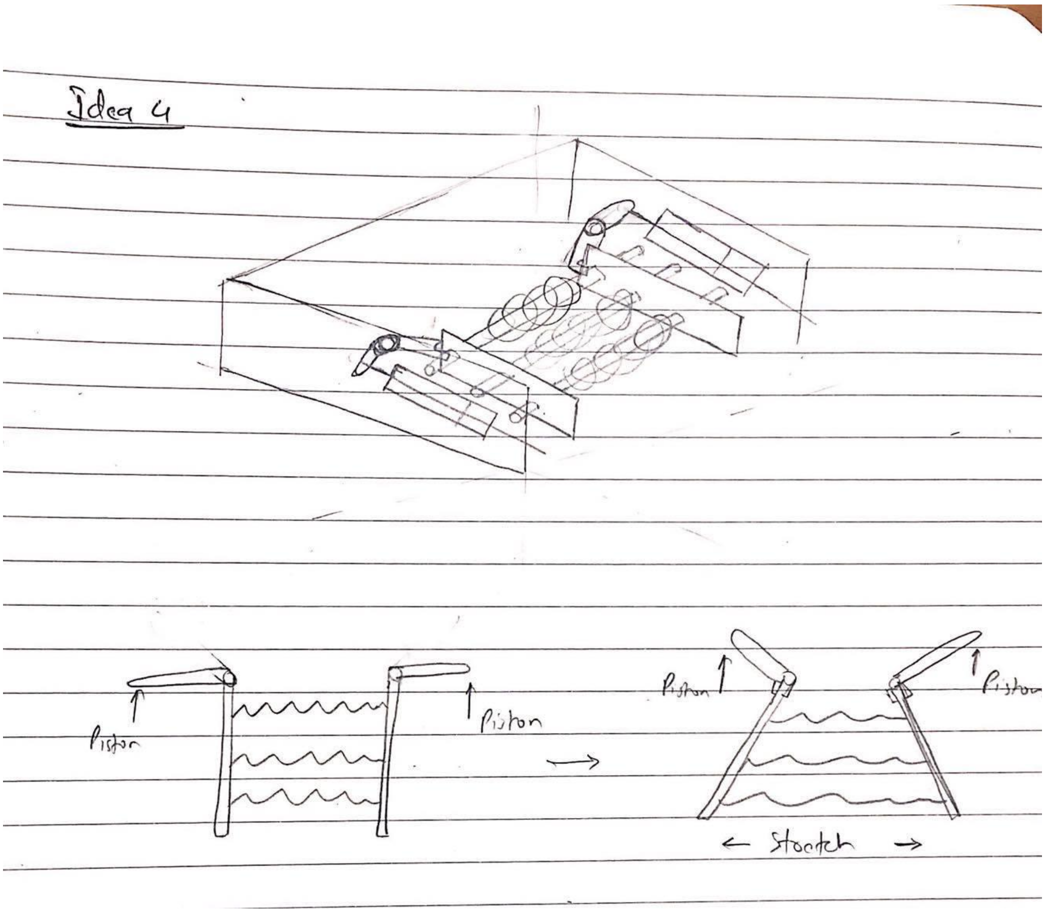

Figure 13. Sketch of idea 4.

8.5 **Comparison of ideas**

Ideas were carefully observed and compared to one another. The first idea seemed to work but consisted many components and was inefficient in terms of mobility. Also, it might not have been able to compress the springs much.

The second idea looked much more stable in terms of force consumption. It was also quick in response since hydraulic cylinders were involved. The use of a hydraulic cylinder, however would increase cost instead of decreasing. Then it would also take extra effort to order custom made cylinders with springs around the rods.

The third idea was simple and consisted of a few mechanical components. It was an easy and efficient method for transmitting force to the springs. It was also stable in terms of strength. In this idea, all the springs could be uniformly compressed.

The fourth idea was also simple and consisted of few mechanical components. But it could not deform springs uniformly. Because of this, the force could not be conserved properly and the conserved force could not be retrieved quickly and easily.

9 FINAL IDEA

The initial ideas were discussed with the thesis supervisor Esa Murtola and Climbstation CEO Kaarle Vanamo (by email). Some pros and cons of ideas were alreadyexplained earlier. The final idea was chosen according to the suggestion of Kaarle Vanamo. From all the ideas that were presented here, Idea 3 was chosen to be developed for the final idea.

9.1 3D model of mechanism

9.1.1 Full-body model

The top view of a climbstation is shown in Figure 14. The springs are placed according to the instructions given by the company. Two connecting arms, cams, spring-walls, cylinders, piston-rods can be seen aligned as one mechanism.

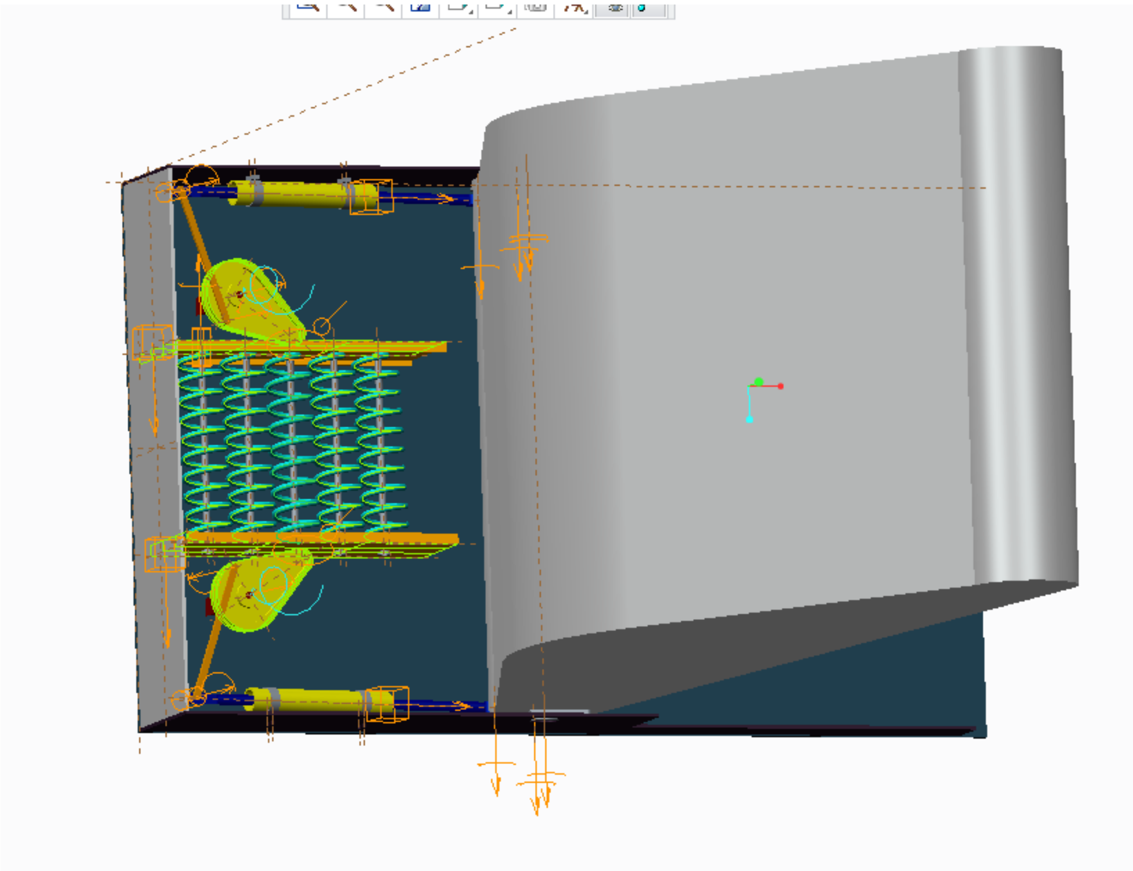

Figure 14. 3D model of climbstation with new mechanism.

9.1.2 Orientation

3D model showing the orientation of climbing wall and position of cam and piston-rod are shown in Figure 15 & 16.

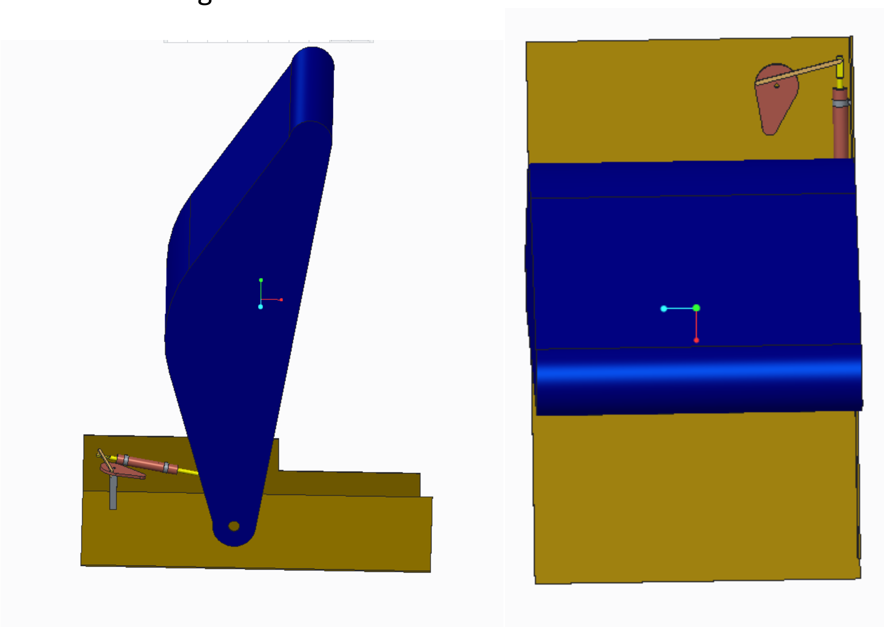

Figure 15. Side view (left) and top view (right) of 3D model when the wall is in standing position.

In Figure 15, standing position of the wall is shown along with the view of the cam and the piston-rod in their initial positions.

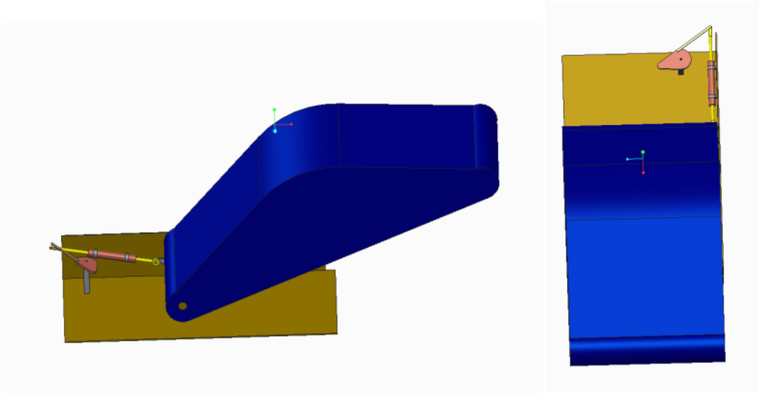

Figure 16. Side view (left) and top view (right) of 3D model when the wall is in tilted position.

In Figure 16, the tilted position of the wall is shown along with a view to the positions of the cam and the piston-rod. As seen in the Figure 16, the piston-rod travels further than the position of the current back-wall.

9.1.3 Spring-wall

The spring-wall encloses the springs. The cross-section was designed as C-shaped to withstand a higher load. One end of the spring-wall had a small extension which acted as a sliding connector with the back-wall.

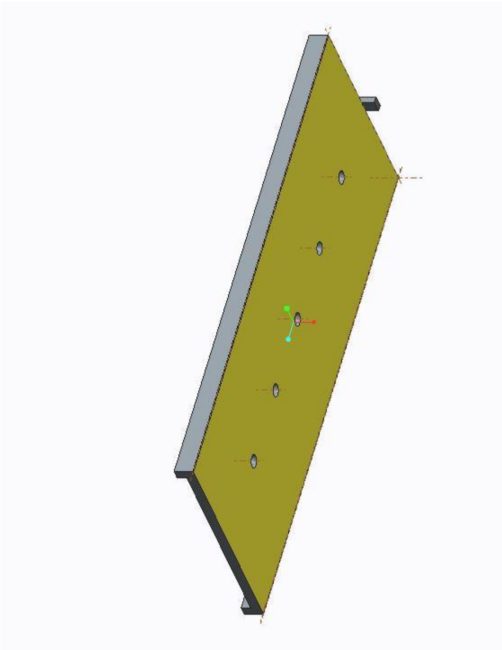

Figure 17. 3D model of Spring-wall.

9.1.4 Cam

Cam was the most important component for the final idea. Figure 18 shows two different versions of the cam. The one on the left side is the early version. Later the shape was improved and a better version is shown on the right side.

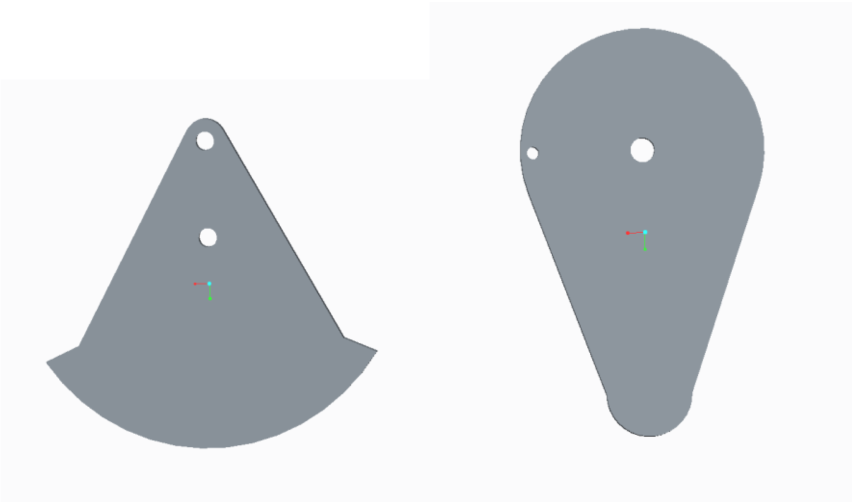

Figure 18. 3D model of initial cam shape (left) and updated cam shape (right).

Stress analyses on the cam were performed using the ANSYS Workbench. After each analysis the shape was improved and the final shape was achieved in the end.

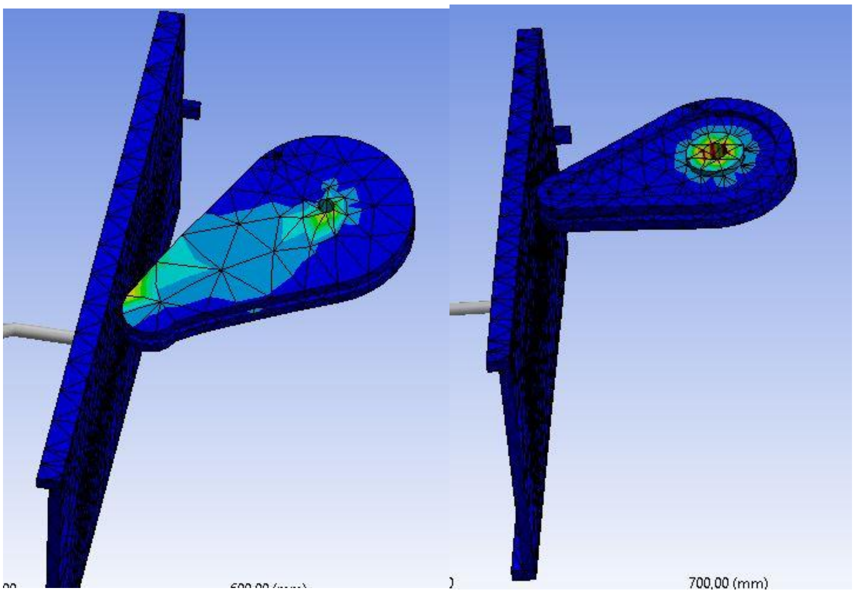

Figure 19. 3D model of the cam with a cut in the middle (left) and final shape of the cam (right).

The purpose of the mechanism was to transmit the force from the wall to the springs and vice-versa. For this purpose, rotation of the cam was an initial requirement. The first task was to place the cam into a suitable position.

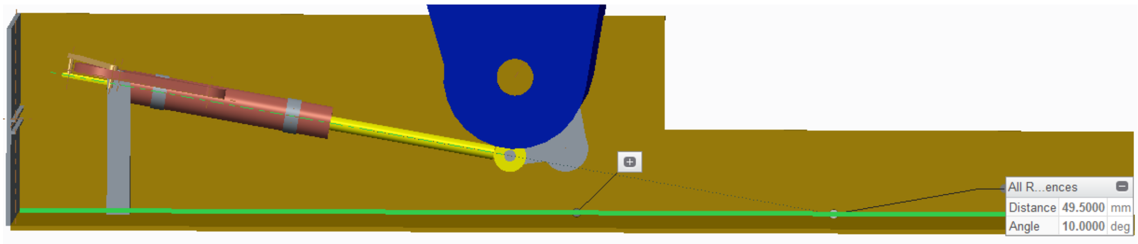

Figure 20. Side view showing the orientation of cam and cylinder.

As shown in Figure 20, the cam had to be aligned with the plane in which the cylinder was positioned. The plane in which the cam and the cylinder were positioned, was tilted 10 degrees with respect to the horizontal plane of the frame. The cam rotated in a circular path. The radius of that circular path was the length of the lobe, which was 275 mm. Because of this, the center of cam was placed at a distance of 342 mm from the cover of the frame at the x-axis. The distance from the back-wall to the center of the cam was 217 mm, since the cam did not have any motion on that side. Based on the calculations, it was found that the maximum angle of the cam with respect to the y-axis was 66 degrees.

9.1.5 Stand

A stand was designed and positioned to support and align the cam in the required axis as seen in Figure 21. The height of the stand was 310 mm. At this height, the cam was aligned with the piston-rod with the connecting rod. The shape of the stand could be further improved to decrease the weight and increase the stiffness.

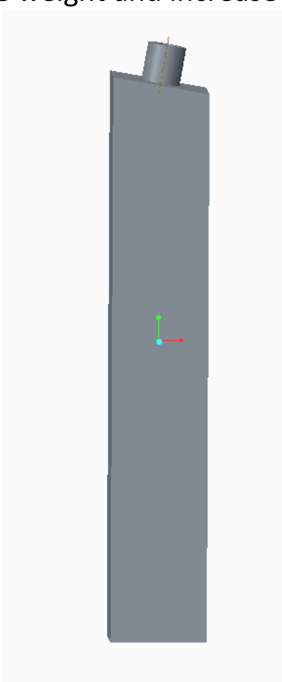

Figure 21. 3D model of stand.

9.1.6 Double-ended piston rod

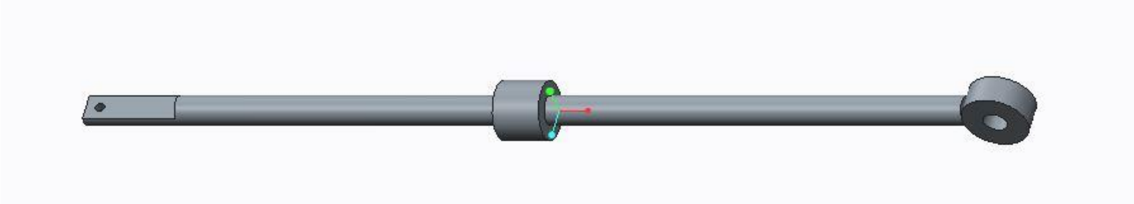

Figure 22. 3D model of double-ended piston rod.

The force to control the wall had to be transmitted back and forth between the wall and the springs. A double rod cylinder was suitable for this purpose as illustrated in Figure 22 so that one end would connect with the wall and the other end to the connector rod. The ends were designed to easily connect with the corresponding components. A double rod cylinder is capable of providing equal forces in both directions as the areas covered by fluid are equal on both sides of the piston.

9.1.7 Connecting arm

Figure 23. 3D model of connecting arm.

A connecting arm was designed as a simple bar which was able to connect with the cam and the piston-rod as seen in Figure 23.

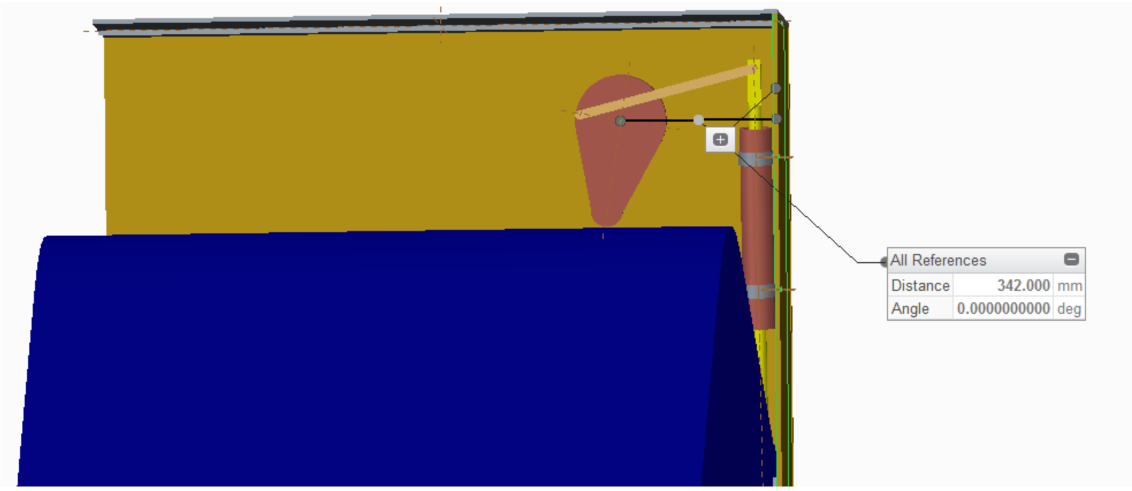

Figure 24. The distance of stand from side-wall.

After cam, position and motion of connecting arm were determined. Since, the function of connecting arm is to synchronize the motion of cam and piston-rod, determining the length of connecting arm was a tricky job. Hit and trial method was performed until a suitable value was obtained. One end of connecting arm followed the motion of rod and other end's movement was synchronized to cam rotation. After a series of iteration and analysis length of connecting arm was chosen to be 393 mm. One end of the connecting arm was connected to the end of the rod. Another end was connected to the cam at a distance 90 mm from the center of cam along the x-axis.

9.2 **Kinematic modeling**

Sketches in the idea section show the basic working principle of the mechanism. After that, the mechanism was analysed to see if the desired movement was achieved. In order to achieve the desired movement, the components must work properly. For this purpose, the kinematic diagram of the mechanism was drawn to perform kinematic modeling. Also, the degree of freedom was computed.

In the kinematic diagram, parts were represented in skeleton form to see only the dimensions that affected the movement of the mechanism. Parts were drawn as lines or geometrical shapes to a scale proportional to the actual mechanism. Links were represented by numbers and joints were represented by letters.

Frame:
The walls and floor of the climbstation were considered as the frame. The position and motion of remaining links were calculated with reference to the frame. The frame is considered as link 1.

Remaining links:
Remaining links of the mechanisms were determined,
Link 2: Piston rod
Link 3: Bar connecting cam and piston

Link 4: Cam
Link 5: Spring-wall

<u>Joints</u>:
Joint A: Joint connecting the piston and the connecting arm
Joint B: Joint connecting the connecting arm and the cam
Joint C: Joint connecting the cam and the frame
Joint D: Joint connecting the cam and the spring-wall
Joint E: Joint connecting the spring-wall and the frame
Joint F: Joint connecting the piston-rod and the cylinder

Joint A, B and C represented primary joints and joint D represented higher order joint.

<u>Points of interest</u>:
Movement of the piston was considered one point of interest, Y.
Movement of spring-wall was considered another point of interest, X.

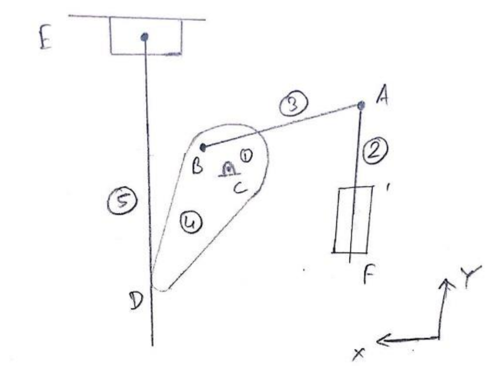

Figure 25. Kinematic Diagram of Mechanism.

<u>Mobility</u>:
We have five links, three pin joints, two sliding joints and one high-order joint
$n = 5$
$j_p = 5$
$j_h = 1$

From Greubler's equation;

$$M = \text{degrees of freedom} = 3(n-1) - 2j_p - j_h$$
$$= 3(5-1) - 2\times5 - 1$$
$$= 1 \text{ D.O.F}$$

9.3 **Static calculations**

After 3D model was made, series of calculations was performed to check the functionality and strength of the mechanism. The first static calculation was performed to check the movement of spring-wall. Spring-wall movement depended on the amount of rotation, the cam could make. In the beginning, it was necessary to calculate maximum moment, the cam beared at point C.

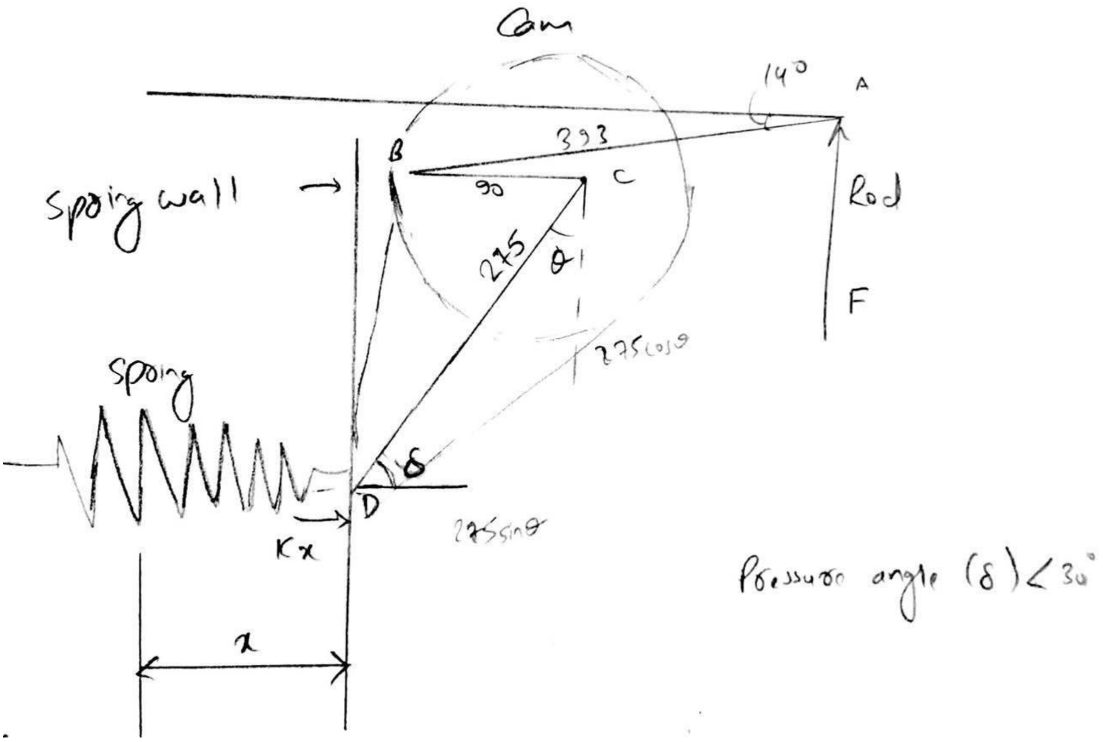

Figure 26. Free-Body Diagram of the mechanism at the initial position.

Given

$a := 275$

$x := a \cdot \sin(\theta) - 200$

Moment

$M(\theta) := k \cdot x \cdot a \cdot \cos(\theta)$...equation 1

Where,

a = distance from the center of the cam to the tip of cam or length of CD

x = distance moved by the spring-wall

θ = angle between CD and y-axis

At minimum,

$dMd\theta(\theta) := \frac{d}{d\theta} M(\theta)$

$$\frac{d}{d\theta}M(\theta) \text{ simplify } \rightarrow 55000 \cdot k \cdot \sin(\theta) - 75625 \cdot k \cdot \left(2 \cdot \sin(\theta)^2 - 1\right)$$

For maximum,

$$dMd\theta(\theta) = 0 \text{ solve}, \theta \rightarrow \begin{pmatrix} \operatorname{asin}\left(\frac{\sqrt{258}}{22} + \frac{2}{11}\right) \\ \operatorname{asin}\left(\frac{2}{11} - \frac{\sqrt{258}}{22}\right) \\ \pi - \operatorname{asin}\left(\frac{1}{22} \cdot \sqrt{258} + \frac{2}{11}\right) \\ \pi - \operatorname{asin}\left(\frac{2}{11} - \frac{1}{22} \cdot \sqrt{258}\right) \end{pmatrix} = \begin{pmatrix} 65.773 \\ -33.25 \\ 114.227 \\ 213.25 \end{pmatrix} \cdot \deg$$

Therefore, the maximum value of θ was approximately 66 degree when 'a' was 275 mm. This showed that cam beared maximum moment at C when the angle between the lobe center- line and y-axis was 66 degrees.

At Maximum,

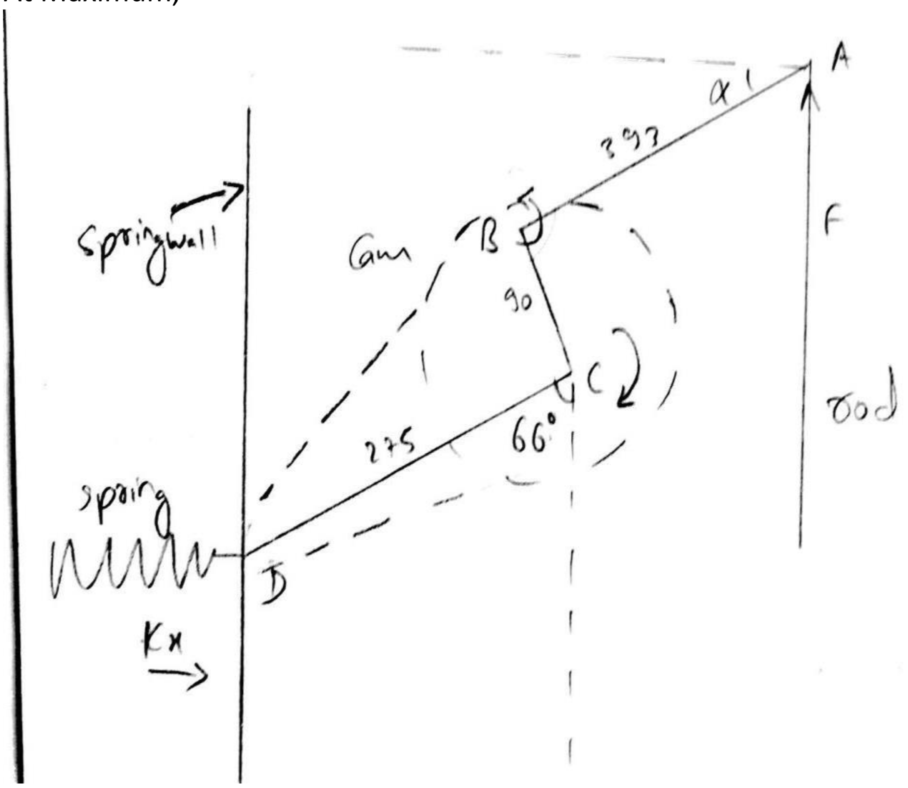

Figure 27. Free-Body Diagram of Mechanism at the final position.

Figure 27 shows the orientation of components when maximum force was applied from the rod. At this condition, the maximum distance travelled by the spring-wall was calculated.

$$\Sigma M_c := k \cdot x \cdot 275 \cdot \cos(66) + F \cdot 393 \cdot \cos(\alpha) = 0$$

Given,
k = 28.95 N/mm for one spring
F = 30 KN
α = 35 degree

The force 30kN was the maximum force that would be applied to springs. The spring constant value was provided by the company. The value of α was taken with the help of Creo from 3D model. After solving for x value, result obtained
x= 994.17 (for 3 springs)

The value x represented the movement of spring from both sides. Since, the length of springs were 700 mm, above obtained value was too much. Values of x was calculated for 4 and 5 springs,
x= 745.63 (for 4 springs)
x=596.5 (for 5 springs)

Therefore, the result showed it required 5 springs to compress 596.5 mm to handle the load of 30 KN.

9.4 **Path of components**

Once a mechanism was designed, it had to be able to perform the function for which it was designed. In this case, the motion and position of components of mechanism were analysed at first. For this analysis, Mathcad and Creo Parametric were used.

9.4.1 Path analysis with Mathcad

From static calculation, it was found that the lobe center-line of the cam was able to make a maximum angle of rotation of 66 degrees. It was assumed that the initial angle of the cam with respect to its origin to be 17 degrees. As the cam rotated, piston-rod also moved in a straight path. Relation between movement of rod along y-axis and angle θ was given by the equation

$$y(\theta) = \sqrt{393^2 - (90 \times cos\theta + 291)^2}$$

Where,
y(θ) was the distance travelled by piston-rod with respect to the rotation of the cam.

When movement of the cam was from its minimum angle to maximum angle, movement of y(θ) was represented by the red line in the graph in Figure 28.

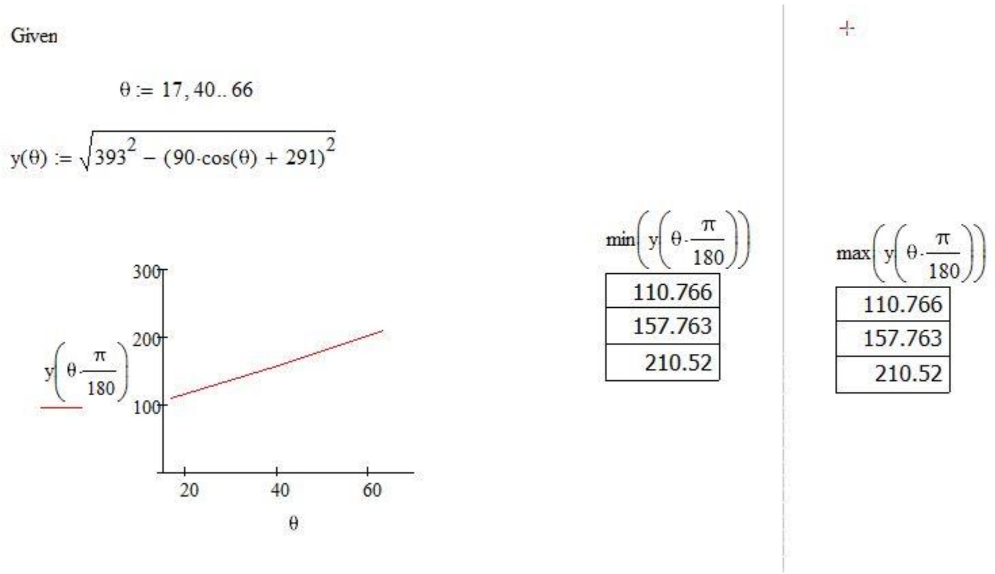

Figure 28. Graph of the path travelled by piston-rod.

The difference between minimum and maximum value was 100 mm. Therefore, piston-rod was allowed to travel 100 mm back and forth. The path of cam and piston-rod were plotted and animated with the help of Mathcad. Figure 29 shows the results that were obtained.

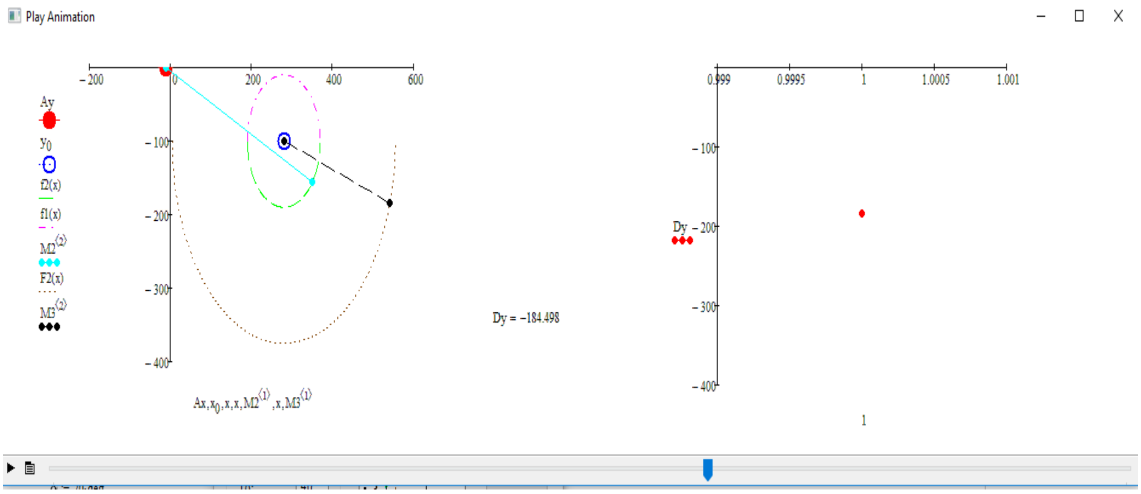

Figure 29. Graph of cam path and the initial position of the cam (Murtola 2017).

The graph on the left-hand side represented the path of piston-rod and cam. The blue line represented connecting arm and the black dotted line represented lobe centre-line of the cam. The red dot represented the joint between piston-rod and connecting arm. It showed the position of piston-rod. The black dot represented the joint between spring-wall and the tip of cam. On the right-hand side of the graph, red dot represented the position of tip of cam. The big circle represented the path of cam rotation.

As seen in Figure 29, everything was in the initial condition. Spring-wall was located at a distance 84 mm from the centre of the cam in the y-axis. End of piston-rod was at the origin.

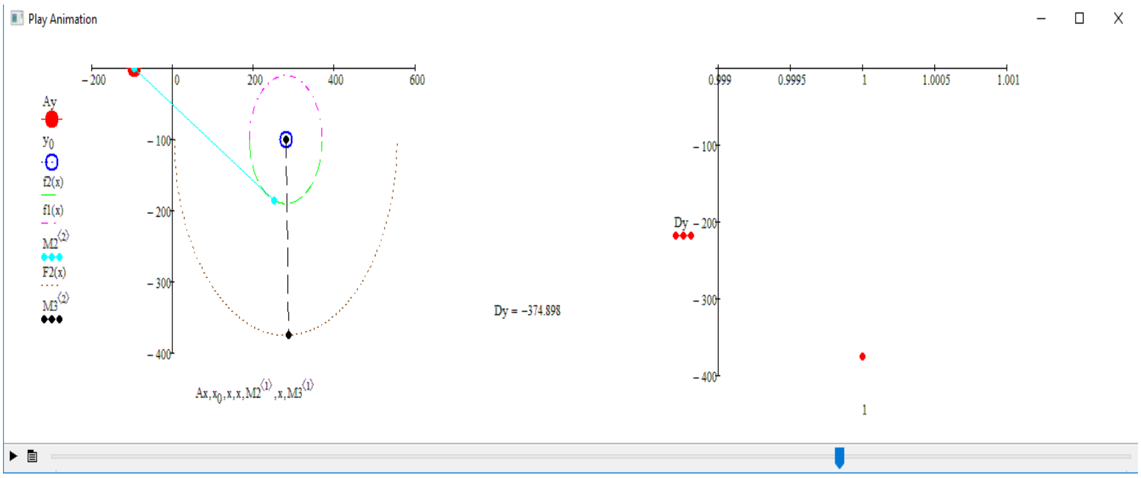

Figure 30. Graph of cam path and the final position of the cam (Murtola 2017).

In Figure 30, spring-wall was pushed to the maximum limit. This distance was 274 mm from the centre of the cam in the y-axis. End of piston-rod traveled 95 mm in the x-axis.

9.4.2 Path analysis with Creo

Creo was also used for the analysis of path of the cam. The result provided by Creo was more easy to understand. Figure 31 & 32 shows the top and side view of the device and the path of cam in two axes.

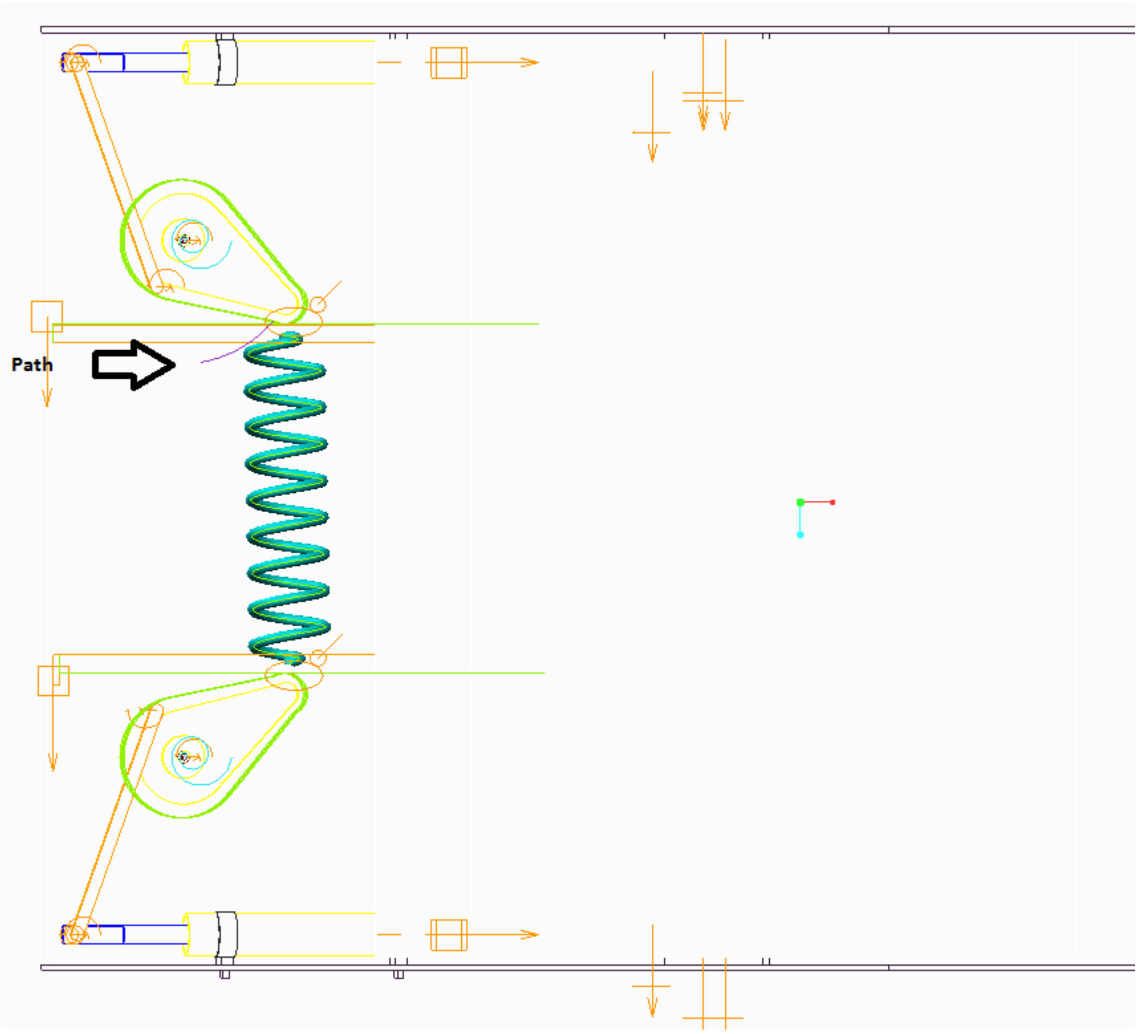

Figure 31. Top view of cam path in Creo Parametric.

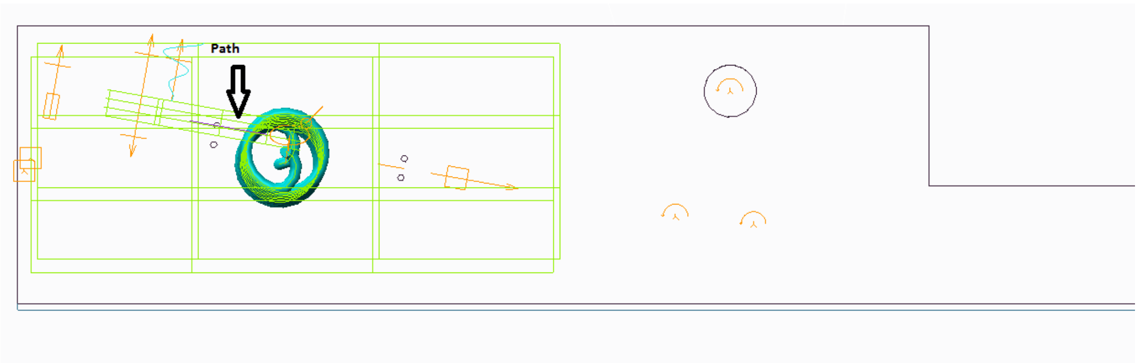

Figure 32. Side view of cam path in Creo Parametric.

9.5 Creo Analysis

Creo offered different applications for a different kind of analysis. In this case, mechanism analysis was used for analysis of force and displacement. Servo motor was assigned at the centre of cam and spring was connected between two spring-walls.

Figure 33 shows the arrangement of the mechanism at the initial condition. Five springs were represented by one spring for the ease of analysis. Spring constant value of 144 N/mm was assigned.

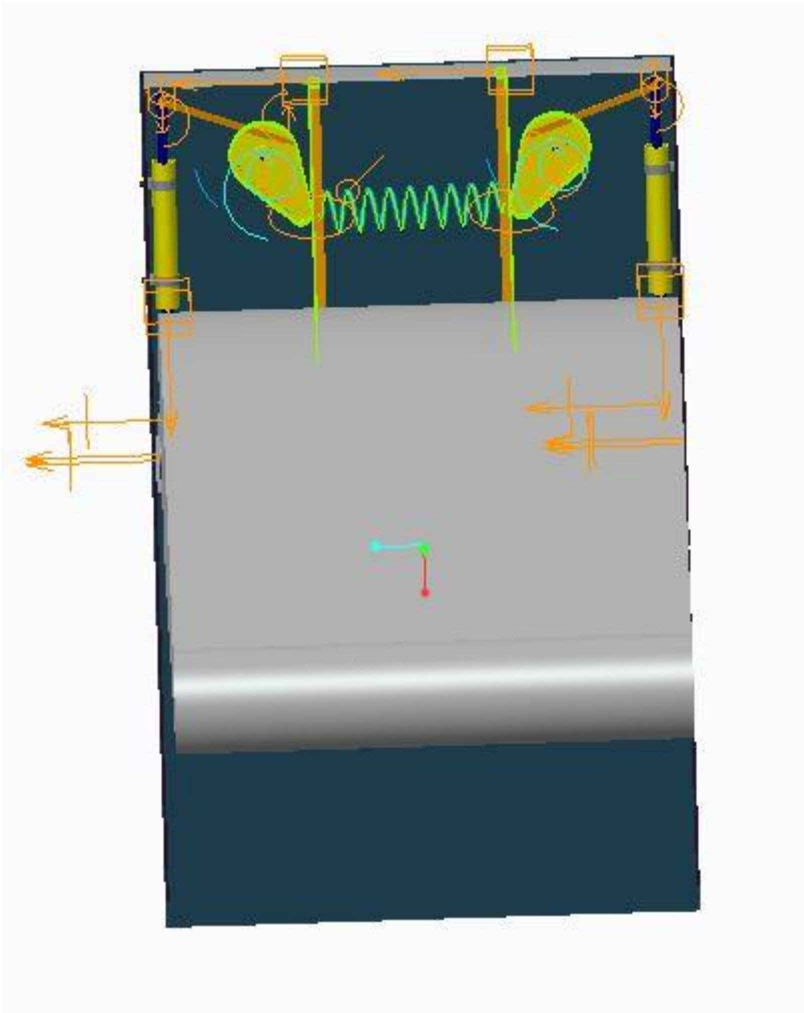

Figure 33. Mechanism at the initial position.

Static and position analysis was performed. Figure 34 shows the arrangement of the mechanism at the end point of analysis.

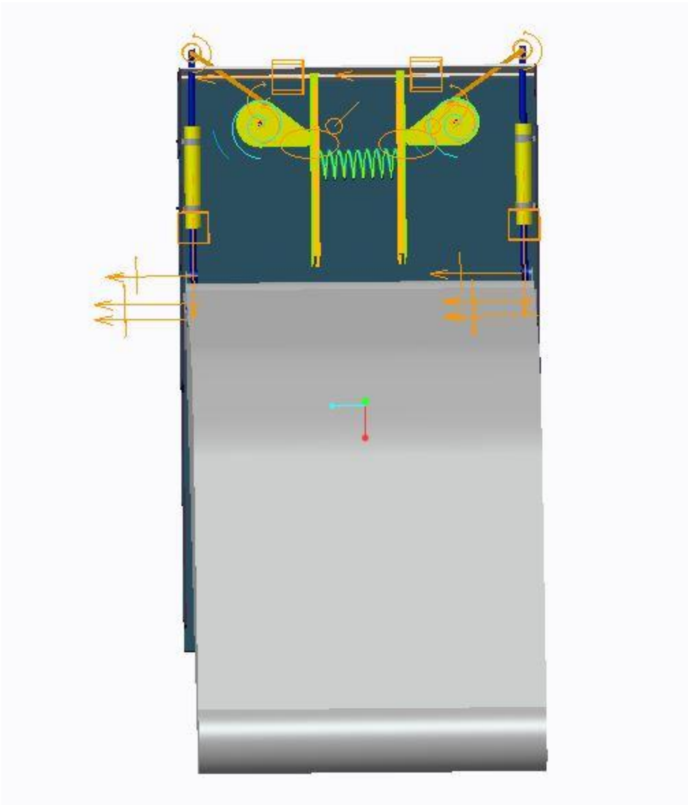

Figure 34. Mechanism at the final position.

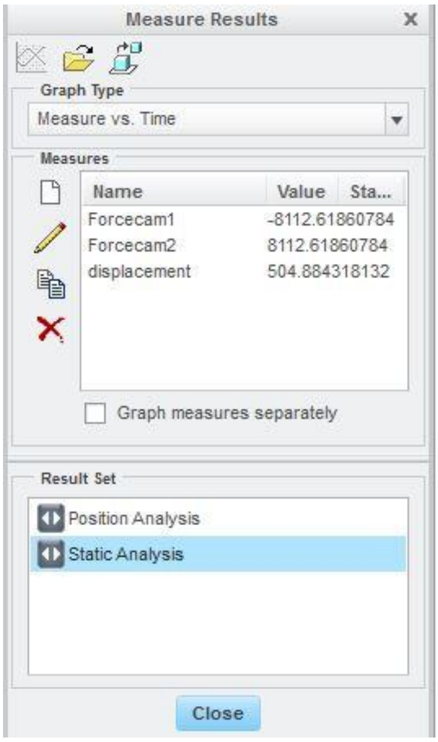

Figure 35. Measure results in Creo Parametric.

Figure 35 shows the result of static analysis. Total force consumed by springs was approximately 16 KN. And springs were compressed up to approximately 504 mm.

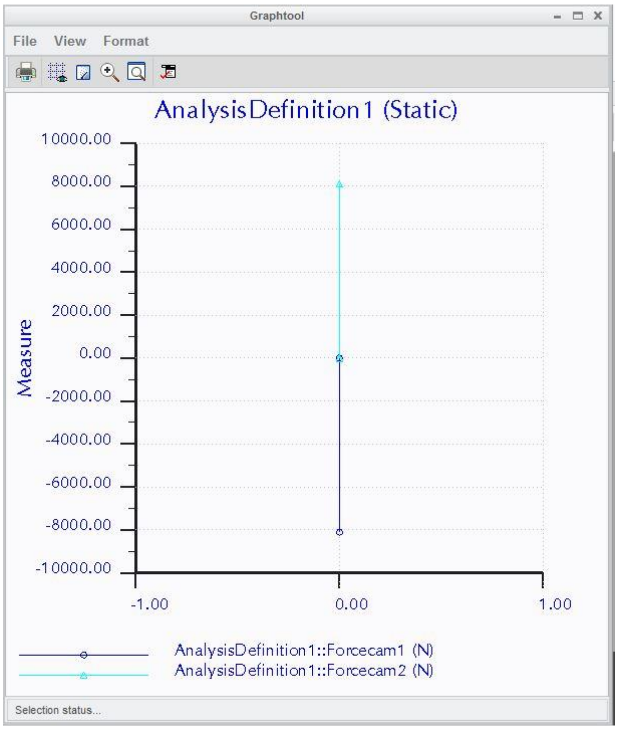

Figure 36. Graph of force consumed by springs in Creo Parametric.

Figure 36 shows graph of the reaction force from the springs acted on the cam. 8 KN force is applied on each cam. Therefore, a total of 16 KN was provided by the springs as they return to their original shape.

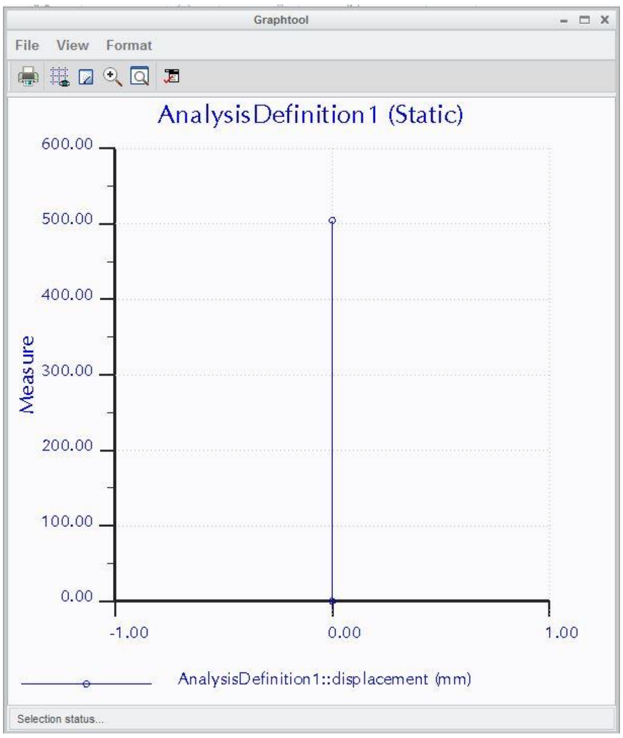

Figure 37. Graph of total displacement of spring-walls in Creo Parametric.

Figure 37 shows the graph of compression of springs. Spring was compressed from both side by the spring-wall movement.

9.6 **Finite Element Analysis**

The sole purpose of using Finite Element Method for this case was to optimize the 3D model to find the best solution. 3D model was analysed using ANSYS. ANSYS workbench offered several analysis systems. Since the aim was to calculate maximum stress, reaction force, and displacement, Static Structural system was chosen. New design modeller was opened and 3D model from Creo was imported as STEP file. Except for two spring-walls and cam, all other components were suppressed. The geometry was meshed with nodes and elements. The model tree in Figure 38 shows a list of boundary conditions, applied loads, and desired solutions.

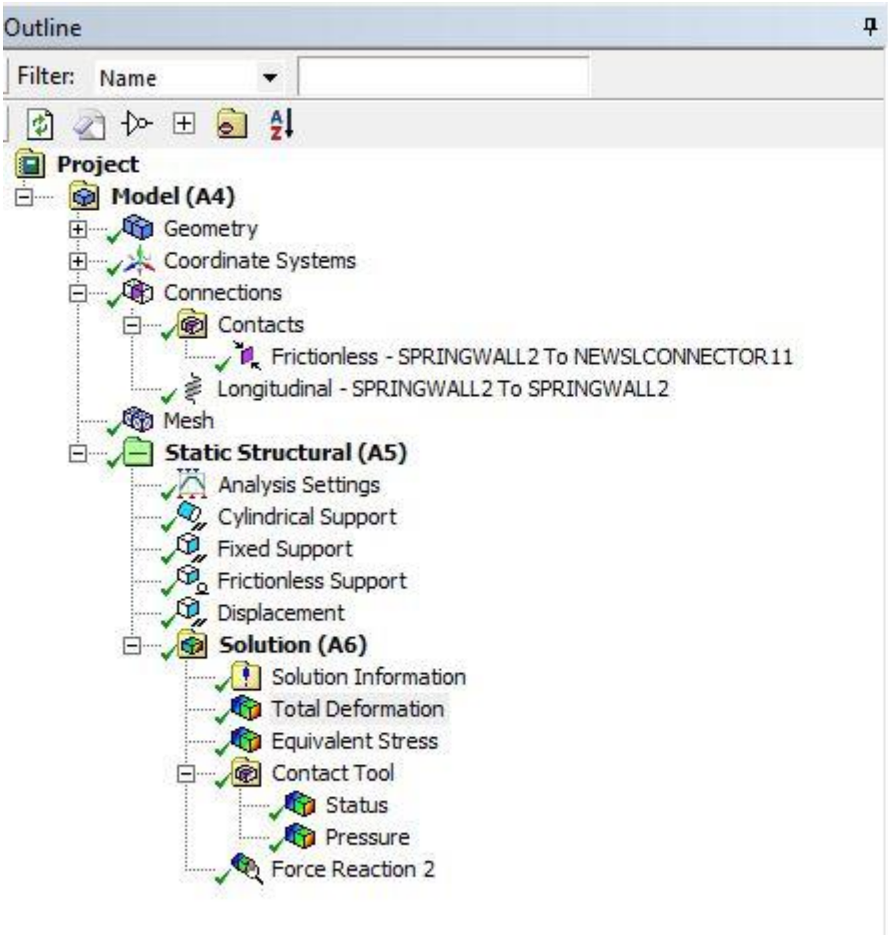

Figure 38. Model tree in ANSYS Workbench 17.2.

Frictionless contact was given between spring-wall and cam. A longitudinal spring was connected between two spring-walls. Cam was supported with a cylindrical support. Right-hand side spring-wall was fixed. Frictionless support was assigned on the boundary of other spring-wall. Cam was subjected to rotation. Desired solutions were total deformation, equivalent stress, pressure and force reaction. Load step options were specified. 50 initial and minimum substeps were assigned along with 1000 maximum substeps.

Details of "Analysis Settings"

Step Controls	
Number Of Steps	1,
Current Step Number	1,
Step End Time	1, s
Auto Time Stepping	On
Define By	Substeps
Initial Substeps	50,
Minimum Substeps	50,
Maximum Substeps	1000,
Solver Controls	
Solver Type	Program Controlled
Weak Springs	Off
Solver Pivot Checking	Program Controlled
Large Deflection	On
Inertia Relief	Off
Restart Controls	
Nonlinear Controls	
Output Controls	
Analysis Data Management	
Visibility	

Figure 39. Analysis settings details in ANSYS Workbench 17.2.

9.6.1 Four Springs

At first, analysis was done with four springs. The pictures below show a single spring because single spring with spring constant value of four springs i.e. 115 N/mm was applied for the ease of analysis. Figure 40 shows the displacement of spring-wall.

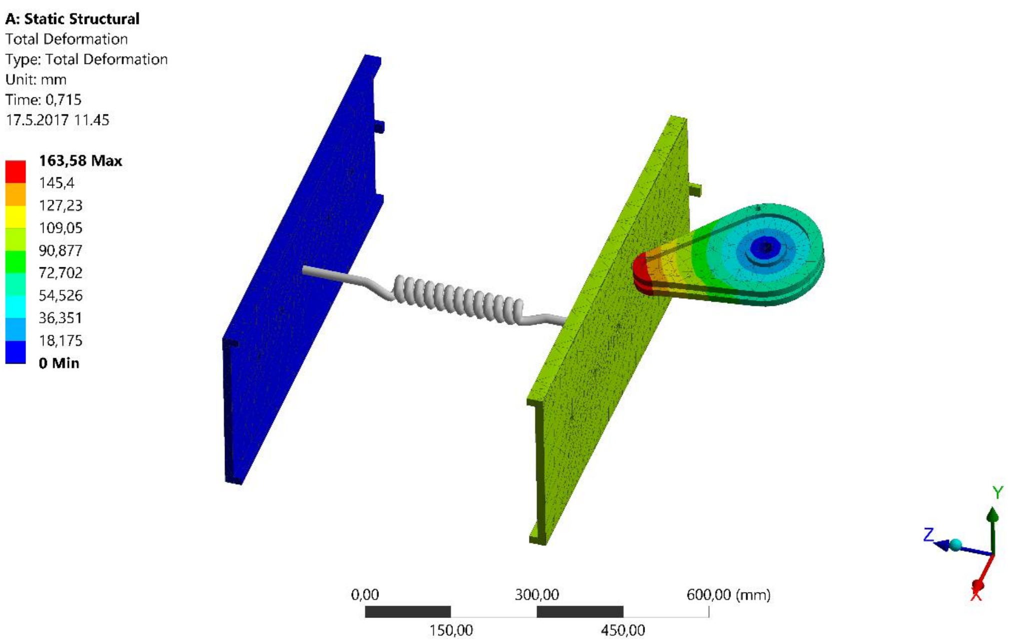

Figure 40. Displacement plot from ANSYS while using four springs.

As one of the spring-wall was assigned to fixed support, 163.58 mm displacement must be multiplied by 2 to get the displacement of both spring-walls. Therefore with four springs, displacement of springs was 327.16 mm.

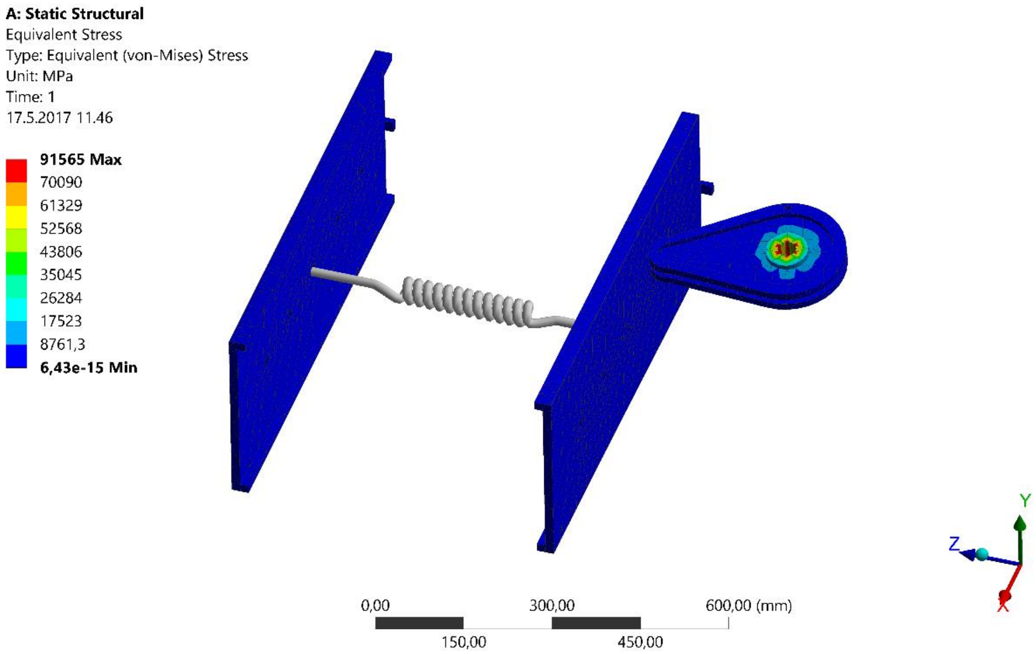

Figure 41. Stress plot from ANSYS while using four springs.

Maximum stress was found to be at the centre of the cam.

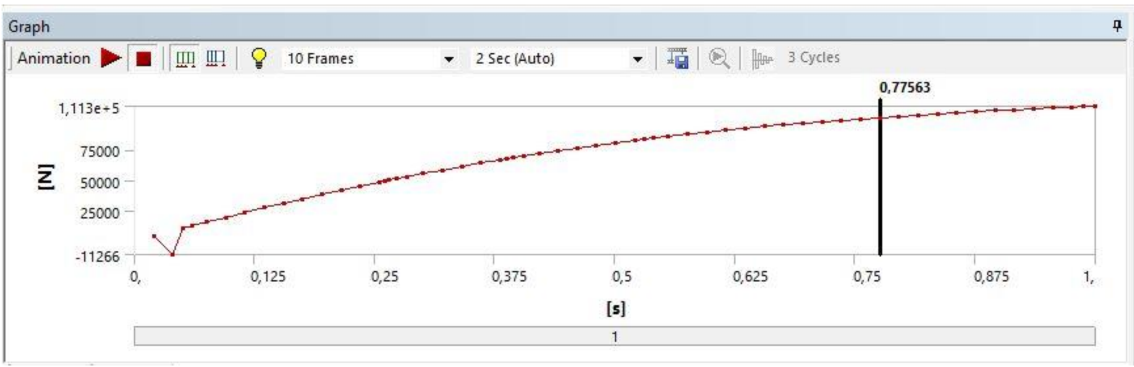

Figure 42. Graph of the reaction force from ANSYS while using four springs.

The force stored by spring when using four springs was shown by the reaction force which was 11.266 KN.

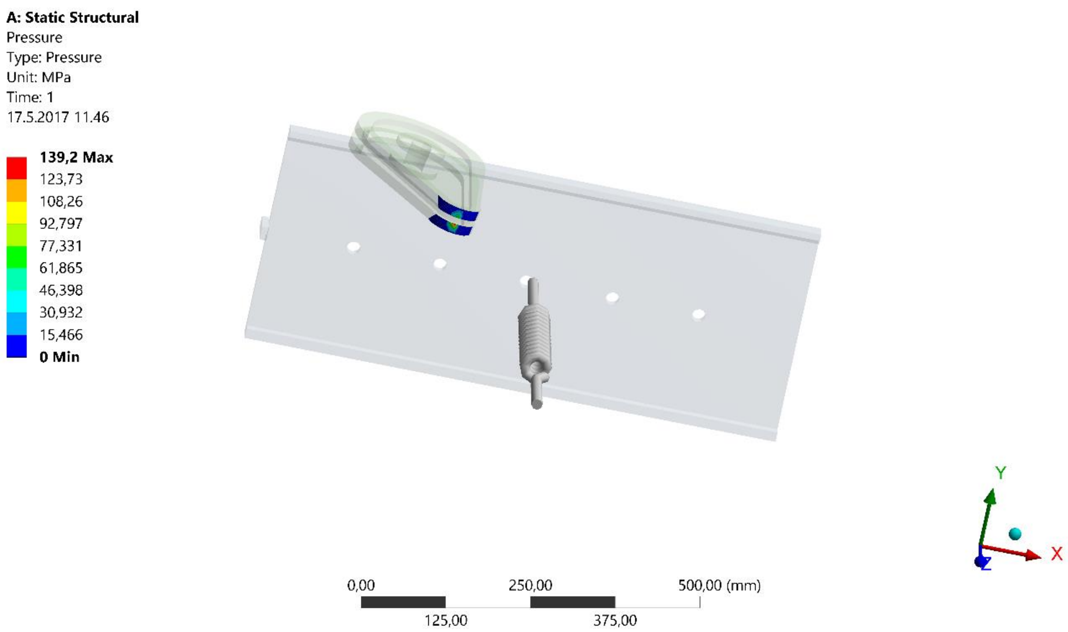

Figure 43. Pressure plot from ANSYS while using four springs.

Maximum contact pressure between cam and spring-wall (follower) was 139.2 MPa.

9.6.2 Five Springs

After a test with 4 springs, analysis was done with 5 springs. The pictures below show a single spring because single spring with spring constant value of five springs i.e. 144 N/mm was applied for the ease of analysis. Figure 44 shows the displacement of spring-wall.

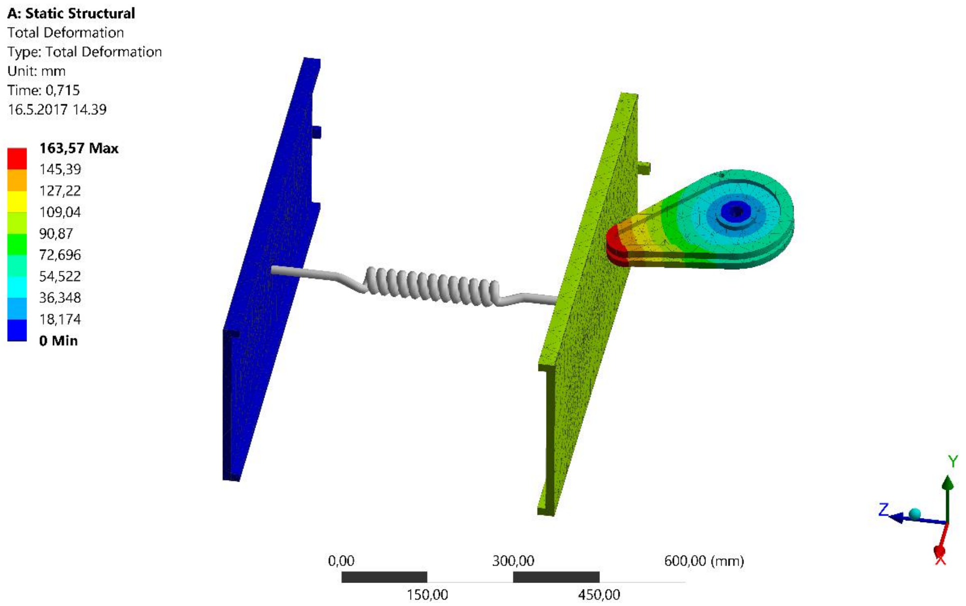

Figure 44. Displacement plot from ANSYS while using five springs.

Again springs were displaced to 327.16 mm.

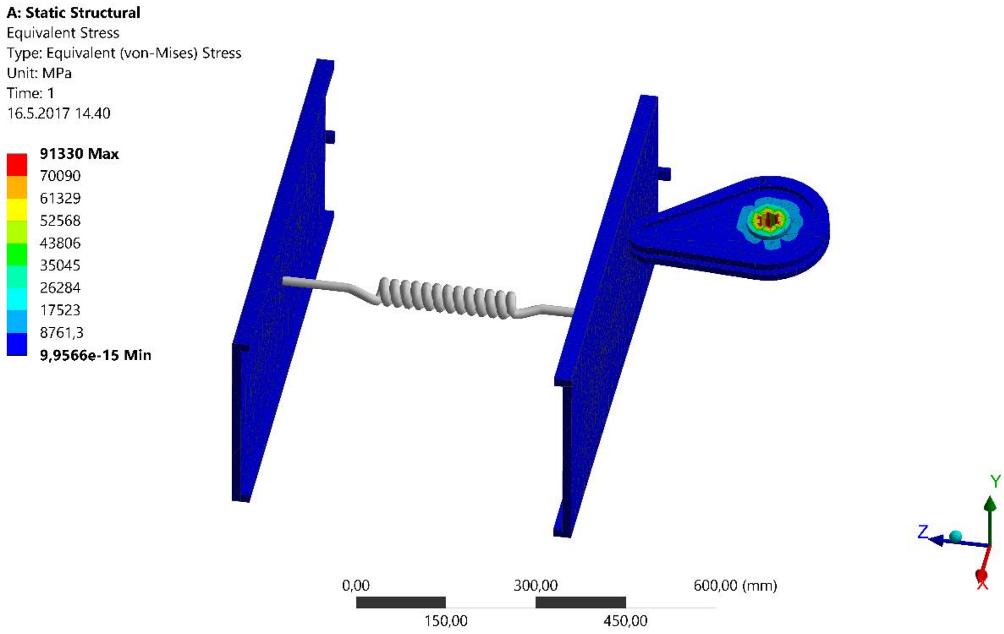

Figure 45. Stress plot from ANSYS while using five springs.

Maximum stress was at the centre of the cam and was a bit less than that of previous analysis with four springs.

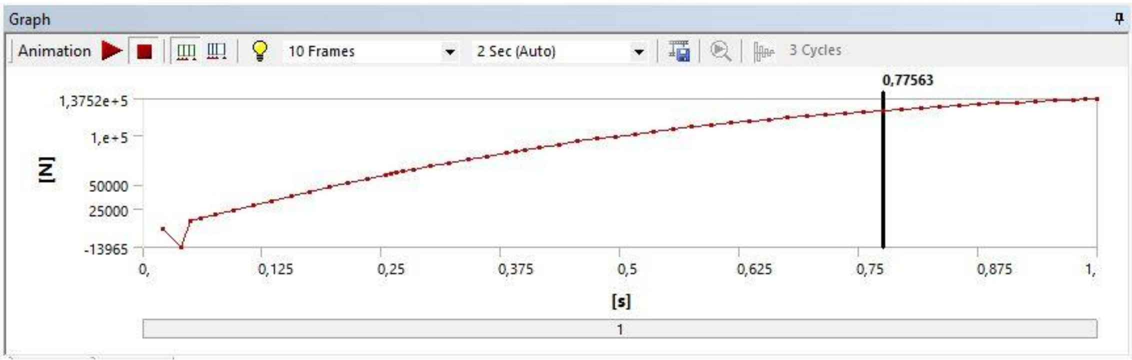

Figure 46. Graph of force reaction from ANSYS while using five springs.

The force stored by spring when using five springs was shown by the reaction force which was 13.965 KN.

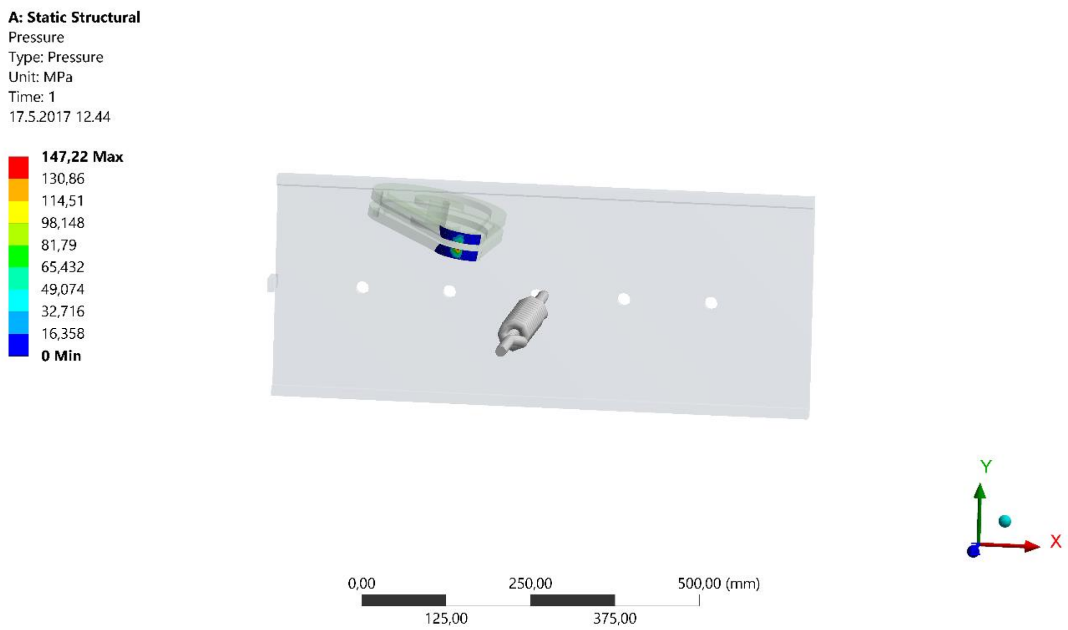

Figure 47. Pressure plot from ANSYS while using five springs.

Maximum contact pressure between the cam and the spring-wall was 147.22 MPa.

9.7 Comparison Of Results

Table 1 shows a comparison between the results obtained using Creo Parametric and the ANSYS Workbench when five springs were used.

Table 1. Comparison of results obtained from Creo and ANSYS.

	Creo Parametric	ANSYS Workbench
Force consumed by springs	16 KN (Approx.)	14 KN (Approx.)
Displacement of springs	504 mm (Approx.)	327.16 mm (Approx.)

10 CONCLUSION

The target of Joyride Games Oy is to have people personally own a climbstation, which requires a deduction to the cost of the device. Replacement of expensive motors with cheaper components that can perform the same function could be pivotal for achieving this target. An electric motor is undoubtedly an efficient and reliable component for any automated device. In a world full of innovations and endless possibilities, however, an alternative idea always makes its way to compete with the best options.
Although such an idea of replacing the electric motor with mechanical springs looked abstract at the beginning, this project was able to demonstrate that it is possible in a clear and convincing way. In this thesis, I demonstrated some ways of using mechanical

springs as alternatives to electric motors. Everything started from scratch and a potential idea was developed from a sketch to a digital prototype (3D model) and analysed for its function and strength. A mechanism was designed and a kinematic analysis was done, the result of which ensured me that it performed the desired function. The mechanism had one degree of freedom and could be driven by one component. A force analysis was conducted using static calculations and software such as Creo Parametric. A finite-element analysis was performed in the ANSYS Workbench. The results gained from these analyses showed that the mechanism was not yet capable of handling a force of 30 KN. However, it confirmed that the mechanism could successfully handle a force of 14-16 KN.

To conclude, this thesis lays a solid foundation for this topic and shows a direction for future designers and researchers. I had a great learning experience and explored many topics which were new to me.

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SPECIFICATIONS OF SPRING

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Finland

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Fax: +358 207 69 9332
E-mail: juuso.virtanen@meconet.net

Date: 15.8.2016
Time: 15:16:49
Initials:

Spring Type: Round Wire Compression

Designed To:	EN 13906-1: 2002	
Tolerance Standard:	EN 15800: 2010	

Material

EN 10270-1 Drawn		
Youngs Mod (E):	206000	N/mm^2
Rigidity Mod (G):	81500	N/mm^2
Density:	,00000785	Kg/mm^3
Unprestress:	0-45	%
Prestress:	45-56	%
End Type:	Closed and Unground	
Dead Coils:	1,50	
Tip Thickness:	100,00	%
End Fixation:	Not Available	

Design Parameters

Wire Diameter:	16,00	mm	
Outside Diameter:	120,00	mm	
Total Coils:	22,00		
Spring Rate:	28,95	N/mm	(Calculated)
Free Length:	700,00	mm	

Calculated Data

Solid Length:	368,00	mm
Min. Length (static):	421,59	mm
Min. Length (dynamic):	448,38	mm
Solid Load:	9612,4	N
Solid Stress:	621,51	N/mm^2
Stress Factor:	1,22	
Active Coils:	20,50	
Spring Index:	6,50	
Helix Angle:	5,63	Deg
Buckling Possible:	Not Applicable	
Buckling Definite:	Not Applicable	
Spring Pitch:	32,20	mm
Inside Diameter:	88,00	mm
Mean Coil Dia.:	104,00	mm
Wire Length:	7221,0	mm
Weight / 100:	1139,7	Kg
Natural Freq:	1570,0	RPM

Stress Data

	Upper Tensile	Solid	% Tensile Operating Positions 1
SL	NO DATA		
SM	1230	51 P	46 P
DM	1230	51 P	46 P
SH	1390	45 U	40 U
DH	1390	45 U	40 U
Specified			

Operating Data

	Operating Positions 1
Length (mm)	400,00
Load (N)	8685,9
Deflection (mm)	300,00
Stress (N/mm^2)	562
Stress % Solid	90
Load Tol. Grade 1 (N)	265,41
Load Tol. Grade 2 (N)	421,28
Load Tol. Grade 3 (N)	674,05
O.D. Expansion (mm)	0,498

SPECIFICATIONS OF SPRING

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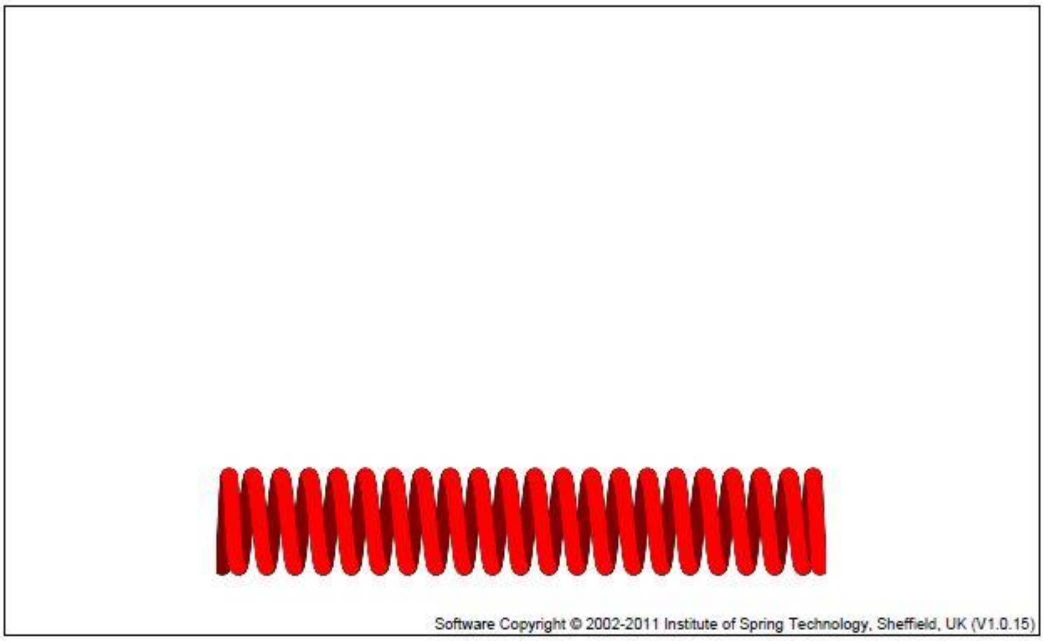
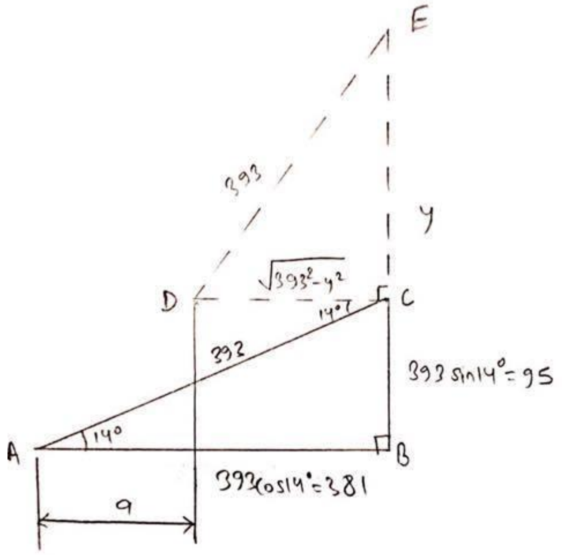
E-mail:	juuso.virtanen@meconet.net	Initials:	

Spring Drawing		Right hand helix	
	Material:	EN 10270-1 Drawn	
d	Wire Diameter:	16,00	mm
D_e	Outside Diameter:	120,00	mm
n_t	Total Coils:	22,00	
R_s	Spring Rate:	28,95	N/mm
L_0	Free Length:	700,00	mm
L_c	Solid Length	368,00	mm
F_{cth}	Solid Load	9612,4	N
Operating Positions			
L_1	Length:	400,00	mm
F_1	Load:	8685,9	N

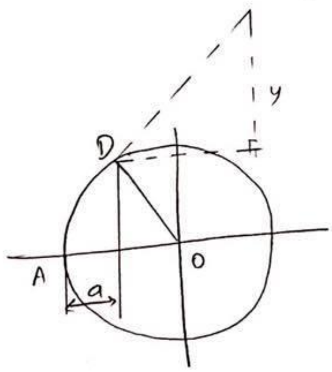


DERIVATION OF EQUATION 2



Length of connecting arm = 393 mm

$$a = 381 - \sqrt{393^2 - y^2} \quad \text{------ equation (1)}$$

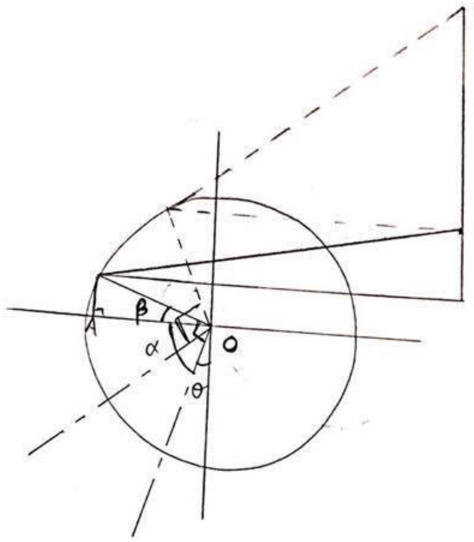


$OA = 90 - a$

or, $OA = 90 - 381 + \sqrt{393^2 - y^2}$ (From equation (1))

$\therefore OA = \sqrt{393^2 - y^2} - 291$ ...... equation 2

DERIVATION OF EQUATION 2



$\alpha = 90 - \theta$

$\alpha = 90 - \beta$

$\therefore 90 - \theta = 90 - \beta$

$\therefore \theta = \beta$

Where,

β = angle between radius (at connection point of connecting arm) and x-axis

θ = angle between center-line of cam and y-axis

Now,

$$\cos\beta = \frac{OA}{90}$$

or, $$\cos\beta = \frac{\sqrt{393^2 - y^2} - 291}{90}$$ (from equation ②)

or, $$90\cos\beta + 291 = \sqrt{393^2 - y^2}$$

or, $$(90\cos\beta + 291)^2 = 393^2 - y^2$$

$$\therefore y = \sqrt{393^2 - (90\cos\beta + 291)^2}$$

$$= \sqrt{393^2 - (90\cos\theta + 291)^2}$$