Glass-Reinforced Plastic Springs for Linear Actuators

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Abstract

This Project investigates the use of glass reinforced plastic (GRP) leaf springs as a replacement for spiral steel springs. Springs are for example used as an elastic element in a Linear Multi-Modal Actuator (LMMA). They are for instance placed in a knee joint of a walking robot. This actuators power the leg and allow the robot to walk and jump. In this report the development and evaluation of leaf springs with both linear and non-linear progressive spring characteristics is presented. Also a hopping experiment was made to evaluate the use of this leaf springs for a jumping robot. For that purpose a series elastic actuator was designed which has a similar operation principle as the LMMA.
Acknowledgement

First of all, we would like to thank Prof. Fumiya Iida for the opportunity to work on this project but also for his support and understanding during the whole process. Also many thanks to Nandan Maheshwari for his help, guidance, doing most of the orderings and always having the right equipment.
A very special thanks we would like to give Fabian Guenther who helped getting started in this project. Also his support in the developing process of the GRP springs is very much appreciated. At this point we would like to thank Dr. Gerald Kress for his help analyzing the results from the spring test.
Big thanks also to the guys from the workshop, in particular Pascal Wespe and Alessandro Rotta. Last but not least we would like to thank all the staff of the BIRL Lab, especially Derek Leach for his huge support in the testing phase. We could always come to you and ask for assistance. You guys are amazing!
Chapter 1

Introduction

1.1 Motivation

In many applications it is interesting to include elastic elements to the structure. Elastic elements provide damping, compliance and more importantly a capability to store and release mechanical energy. Building up energy when compressing spring and then releasing the spring makes a robot jump very efficiently.

Springs are very old mechanical elements. Spiral springs are known since the early fifteenth century. When they first appeared in watches. In 1676 a british physician, Robert Hooke, discovered the basic principle for mechanical springs. Hooke’s Law as it was named from there on, describes the linear correlation between the displacement of the spring and the resulting force by

\[ F(x) = k \cdot x \]

The linear correlation simplifies the computation of the spring in a mechanical environment. The spring constant \( k \) is specific to the material used in the spring and the geometry of its structure. For example the used material, the thickness of the wire and the lead of the coil.

In some applications it might be more interesting to have a non-linear characteristic. If we look at the properties of natural muscles we find, that they have a non-linear spring like behavior. In bio-inspired robotics we try to mimic biological systems. A spring with natural properties is therefore of great interest.

1.2 Goal of project

Since the first two prototypes of the Linear Multi-Modal Actuator (LMMA) are very big and heavy, we decided to look for ways to make it smaller, lighter and also simpler to manufacturing. The design of the LMMA I and II are well enough for their purpose. But there are some key problems. The massive steel spring is almost 25 % of the overall weight. Also there is systematic problem with spiral formed springs. When compressed, a spiral spring always generates a small turning moment. This turning moment can lead to a jam of the two sliders of our actuator design. The friction increases resulting in a mechanism which gets stuck.

We then came up with the idea of replacing the spirial steel spring with a lightweight glass reinforced plastic (GRP) or carbon fiber (CF) leaf springs. This leaf spring is not only light, but it also compresses without the generation of turning moment. It is also simpler to mount, as it does not need any complicated connectors. Both GRP and CF are comparable to steel in terms of strength and endurance, but are much lighter. The major difference between GRP and CF is that CF is stiffer and even a bit ligther.
Chapter 1. Introduction

The only problem with CF is that conditioning generates dust which is cancer causing when entering the lungs. So for health and simplicity reasons we decided to focus on GRP materials.

In this project we focus on the manufacturing and testing of such leaf springs. Are they suitable replacements of the spiral steel springs? Is there a way how we can design springs for a specific task? Meaning can we design the characteristic curve of a spring in a linear or even in a non-linear progressive way?

1.3 Structure of report

This report is structured as follows: In chapter 2 a short introduction to GRP material is provided. In chapter 3 the focus lies on the manufacturing of the springs. In chapter 4 we describe the development of the series elastic actuator. In chapter 5 we present the results for the spring tests as well as from the hopping experiment. In chapter 6 we draw a conclusion about our work. And finally in chapter 7 an outlook on further work on the project is given.

Basic calculations we did are described in appendix A. Blue prints of mechanical parts of the series elastic actuator can be found in appendix E.
Chapter 2

Introduction to GRP

This chapter introduces the reader to the composite material which we used for this report: Glass Reinforced Plastic (GRP). For construction we used the hand lay-up operation since we do not have the equipment for other construction methods. Section 2.1 provides a short overview on the structure of the material and basic material properties. In section 2.2 some basic limitations of GRP materials are mentioned. In section 2.3 we list miscellaneous applications of GRP materials in modern engineering.

2.1 Structure of GRP

Other than metals like steel and aluminium, GRP does not consist of one (crystaline) material structure, but consists of many fibers. This very long and thin fibers are made of glass. The matrix which holds the fibers together is a polymer resin ([3],[4]). The material can be bought as a pre-made glass fiber fabric of different thickness and structure. The fabric is very cheap compared to steel and aluminium but also compared to other composite materials. Out of the fabric any kind of layers shapes can be cut. The resin is applied when laminating each layer. We mainly distinguish between unidirectional (UD) and crossbred (CB) kind of fabric. The unidirectional fabric has all the fibers in the same direction. The crossbred fabric crosses the fibers in different angles. In particular 45 to 90 degree. In figure 2.1 on the left the a sketch of unidirectional fabric is shown and on the right is the crossbred fabric, which we used for our springs.

\footnote{Sometimes also called Glassfiber reinforced Plastic (GFRP)[4]}
\footnote{e.g. spray lay-up, pultrusion}
Chapter 2. Introduction to GRP

Figure 2.1: Left image: Sketch of unidirectional glass fiber laminate. Right image: sketch of crossbred glass fiber laminate with an angle of 90 degree. The resin, displayed in orange, fully covers the fibers and holds them together.

The resin functions as binding material to hold the fibers together. We used epoxy resin for that purpose. Since the resin itself can not hold much weight the strength of the material comes from the glass fibers. Since each fiber is long and thin it can only withstand strain in direction of the fiber. Therefore the unidirectional fabric is very strong in one direction but lacks of any strength in direction perpendicular to the glass fibers. The crossbred fabric, however, has fibers in both directions equally. Therefore it can be stressed in both directions and is assumed to be quasi-isotropic.

Drawbacks of UD fabric are the anisotropic material properties due to the direction dependency. The cross fibers do also help in holding fibers straight together. Therefore in practice often CB fabric is used eventhough half of the weight is lost due to the fibers which point in the orthogonal direction without immediate use for strength of the material.

2.1.1 Material properties

Figure 2.2 shows a comparison of miscellaneous materials properties. The most interesting comparison is of course between steel and E-Glas which is the material of our glass fibers.

<table>
<thead>
<tr>
<th>Material</th>
<th>Dichte $[g/cm^3]$</th>
<th>Festigkeit $[N/mm^2]$</th>
<th>Reißlänge $[km]$</th>
<th>E-Modul $[N/mm^2]$</th>
<th>spezifisch $[km \times 10^3]$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminium</td>
<td>2.63</td>
<td>620</td>
<td>24</td>
<td>73000</td>
<td>2.8</td>
</tr>
<tr>
<td>Titan</td>
<td>4.61</td>
<td>1900</td>
<td>41</td>
<td>115000</td>
<td>2.5</td>
</tr>
<tr>
<td>Stahl</td>
<td>7.66</td>
<td>4100</td>
<td>54</td>
<td>207000</td>
<td>2.7</td>
</tr>
<tr>
<td>E-Glas</td>
<td>2.50</td>
<td>3400</td>
<td>136</td>
<td>72000</td>
<td>2.9</td>
</tr>
<tr>
<td>S-Glas</td>
<td>2.44</td>
<td>4800</td>
<td>197</td>
<td>86000</td>
<td>3.5</td>
</tr>
<tr>
<td>Carbon</td>
<td>1.38</td>
<td>1700</td>
<td>123</td>
<td>190000</td>
<td>14.0</td>
</tr>
<tr>
<td>Beryllium</td>
<td>1.82</td>
<td>1700</td>
<td>93</td>
<td>300000</td>
<td>16.0</td>
</tr>
<tr>
<td>Boron</td>
<td>2.52</td>
<td>3400</td>
<td>137</td>
<td>400000</td>
<td>16.0</td>
</tr>
<tr>
<td>Graphit</td>
<td>1.38</td>
<td>1700</td>
<td>123</td>
<td>250000</td>
<td>18.0</td>
</tr>
</tbody>
</table>

Figure 2.2: Comparison of material properties of miscellaneous materials used in mechanical engineering [2]

The density of GRP is only 33% of the density of steel but still the stability of glass
fibers are 83% of steel. So GRP fabric is much lighter but almost as strong as steel. The main difference is the rather different E-modulus. The much lower modulus of GRP means that the material is much more flexible. We can see that fact in the different breaking lengths as well.

The amount of energy which can be stored in a spring is the area beneath the characteristic curve\(^3\) of the spring. Therefore for energy storage we are very interested in flexible materials because the more flexible the material the higher the displacement. Since the stability is almost the same, the spring made of GRP can hold similar force without breaking. Figure 2.3 illustrates that fact with a sketch of the characteristic curve of a steel and a comparable GRP spring. One can easily see that the area under the GRP spring is bigger.

![Figure 2.3: Sketch of characteristic curves of a steel spring and a corresponding GRP spring. The area under the curve is the energy which can be stored in the spring.](image)

Other properties are a high electrical resistance and a strong resistance against corrosion ([3],[4]).

## 2.2 Limitations

Besides the numerous advantages of GRP material over steel, there are also some important drawbacks. The list is not complete but covers important drawbacks from our point of view.

- The need for a counterblock. With GRP one can build almost any kind of layer based shape. Only limitation is the counterblock on which each layer is laminated. Especially sharp corners are very difficult to make. But any kind of gap produces air pockets when laminating. Each air pocket greatly reduce stability. In practice spatula is used to cope with that problem.

- Manufacturing is much more time consuming and equipment for autonomous production is expensive. GRP products are often hand made which has its own limitations (precision, repeatability, costs, ...)

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\(^3\)Force over displacement diagram
2.3 Applications of GRP in modern mechanical engineering

GRP is a very versatile material. The material properties and the fact that it is very cheap favored GRP in a variety of applications ([3],[4]).

- Pipes
- Lightweight covers
- (Model) planes
- Lightweight leaf springs for cars
- Rotor blades of wind energy power plants
- Hulk of a boat (e.g. yacht)
Chapter 3

Design of the spring

In this chapter we focus on the design of the springs we used in our actuator. The development of the linear spring is described in section 3.1. In section 3.2 we describe the development of the non-linear spring.

3.1 Linear spring

To design a leaf spring there are many different possibilities. One simple approach is the U shape. It allows both compressing and stretching of the spring. Both is required for a linear actuator in order to operate in both directions. Also - since a counterblock is required - the U shape is simple enough to be manufactured by hand in our own lab.

3.1.1 Computation

The goal was to design a spring that has a similar characteristic curve as the steel springs, namely linear. The force is introduced on the tip of the spring legs. We therefore have a linear increase of the bending moment with respect to the distance from the tip of the spring leg to the back of the spring. Figure 3.1 shows the linear change in thickness we used from the tip of the spring leg to the top of the spring. This allows us to have an equal distribution of the bending moment over the whole spring. We want the back of the spring to be rigid and not bend in order to simplify the computation. Therefore the top has the biggest thickness.

Figure 3.1: Simple CAD concept model of the U shaped leaf spring we designed with a linear decrease in thickness from the top to the tip of the spring leg.
Since the U shape still has bended parts which are difficult to calculate analytically we used a simplified model. In figure 3.2 the simplified model for one spring leg is shown. The rigid back of the spring can be assumed to be a wall. The spring legs then act as beams with a linear change in thickness.

![Figure 3.2: Simple model of one spring leg with linear change in thickness. The rigid back of the spring can be simplified as a wall. The force is applied on the end of the spring leg.](image)

Since the spring is symmetric, calculating one leg is enough. The original steel spring was picked to have maximum displacement at around 100 N Force. Figure 3.3 shows the bending line of the simplified model when applied 100 N force on the beam. All calculations were done using an online FEM tool\(^1\). The computations are not meant to be very accurate but they allow us to roughly estimate required thickness of the spring. The thicker the structure the more stiff the spring becomes.

![Figure 3.3: Picture of the output of the online FEM tool which we used for estimating the required thickness of the spring. Above is the spring leg as we have modeled it. The lower image shows the bending line of the spring leg when force is applied on the end of the bar.](image)

Because this calculations are not very accurate and for testing reasons we then also made springs with half the thickness and with 50% more material. Those springs are denoted in this report as spring type 1.0 for the original, 0.5 and 1.5 for the alternative springs.

### 3.1.2 Counterblock

The first counterblock was cut from a block of styrofoam with a hot wire. After grinding it to a good surface and shape we used a plastic tape to seal it. This step is important in order to prevent the very aggressive resin to attack the styrofoam. During the manufacturing of the first test spring series we experienced a high increase in temperature of the hardener-resin mixture. In figure 3.4 the result after removing the vacuum pump

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\(^1\)http://www.tm-interaktiv.de/BT2D/index.html
9 3.1. Linear spring

is shown. The heat we experienced shranked the styrofoam. The structure was wizened and therefore unusable.

Figure 3.4: First try failed: The result after removing the vacuum bag. The increase in temperature of the resin-hardener mixture caused the counterblock to shrink.

For the next counterblock we then decided to use wood. Wood is still easy to handle by hand with simple tools and very cheap. Thinkable for this task are also milled metallic counterblocks, or shapes made with a rapid prototyping process. But both are much more expensive to produce.

Figure 3.5 shows the second counterblock we built. We cut multiple layers with the desired shape from a wooden (MDF) board. We then glued this layers together and grinded the borders to the exact shape. Again we used a plastic tape to protect the counterblock from the resin and as a separation layer. With this block we were able to produce all three spring type at once. The black markings on figure 3.5 on the right indicate the location of the three springs. The overlapping material in between the markings was then cut away. As it turned out the tape did not separate the spring from the counterblock as we expected, so we used cling film additionally. With cling film the separation was very satisfactory.

Figure 3.5: Pictures of the second counterblock version. The counterblock is made of wood. The tape is used as a separation layer. The black markings indicate the location of the springs. The rest of the material will be cut away.
3.1.3 Layer setup

With the FEM tool we estimated the required thickness of the spring as well as the change in thickness distributed over the whole structure. We used a GRP fabric with a thickness of 0.15 mm. For the thickness of 3.1 mm (thickest part) of the spring this required a count of 20 to 21 layers. For 0.9 mm (thinnest part) 6 layers are required. The thickness of the spring is therefore controlled by the number of layers used. We decided that a change in thickness in discrete steps of 1 cm is enough for this application. We then calculated all necessary layers we need in order to have 8 layers on the tips and 21 layers on top of the spring in the end. According to this setup we cut each layer out of the fabric. Since the resin is hardening in approximately 45 minutes it is essential to have everything in place by the time the lamination process begins.

In order to achieve a good surface quality and stability it is necessary that at least the inner and the outer layer go all the way from one side to the other. Figure 3.6 illustrates how the layers have been arranged for that task. The layers are stacked symmetrically from the longest layer to the shortest and vice versa.

![Diagram of layer layout](image)

Figure 3.6: Sketch of the layer layout. Inner and outer layer are the longest and cover all the way of the spring form. Counting the number of layers one can see that in the middle there are more layers than at the ends of the form. Therefore the effective thickness of the spring varies from the middle to the ends.

For the different types of springs (reference 1.0, alternatives 0.5, 1.5) we simply multiplied the number of layers by 0.5 or 1.5, respectively. Half layers have been rounded up. See appendix A for detailed informations regarding the layer setup. The 0.75 and 1.25 type of spring from the second set also refer thickness compared to the reference spring (type 1.0).

Each layer had a width of 50 mm although the spring was designed to be 30 mm wide. This way the manufacturing process was very tolerant to small errors. In the end we could just cut stripes of 30 mm width to get the springs.

3.1.4 Manufacturing of the spring

The basic procedure for making the GRP springs is simple. Each layer of the grp material is placed separetely on the counterblock. Between each layer we apply resin on the previous layer. The resin gets soaked in into the GRP fabric until it is saturated. The purpose of the resin is to hold the fibres of the GRP material together. But it does not hold much weight and does therefore not contribute anything to the stability of the resulting material. We therefore need to apply as few resin as possible but still as much as required. Since the resin still has weight and is therefore making the structure heavier.
Once all layers are laminated we placed the counterblock in a vacuum bag and activated the vacuum pump for about 4 hours. This process soaks out redundant resin and gets rid of small pockets of air inside the structure of the spring. The resin needs about 24 to 48 hours to get fully hardened.

Afterwards it is possible to further process the springs: cutting stripes of 30 mm, grinding the sides and breaking the edges. Figure 3.7 shows a GRP leaf spring after cutting and grinding. The fact that they are crimped is ugly and needs to be dealt with. The ripples came from the vacuum bag. When the air gets sucked out, the whole bag collapses and shrinks together. This causes the soft surface of the GRP spring to deform. We tested the effect of the ripples on the spring in section 5.1.1.

![Figure 3.7: GRP spring after cutting and grinding. The red arrows point at one of the ripples in the outer layers of the spring from the first set.](image)

Since the U shape of the counterblock is much more complex than a flat plane and the three different spring types have different thicknesses it is impossible to use a second counterblock on top to avoid ripples. But there are other thinkable ways to reduce the ripples.

We significantly reduced ripples in the outer layers by using a additional layer of torn away fabric. The torn away fabric is much stiffer than the GRP fabric. As it turned out, this was enough to avoid deformation when shrinking the vacuum bag. Figure 3.8 presents a pair of our second set of springs. The surface is much nicer and there are no ugly ripples anymore.

![Figure 3.8: Photograph of a pair of GRP leaf springs from our second set.](image)

For the second set of GRP springs we analyzed the test data from the first spring set (refer to section 5.1). The 0.5 type from the first set seemed a bit too soft and the 1.5 type a bit too rigid. So we designed the second set to contain a type 1.0 reference spring, as well as type 0.75 and 1.25 with slightly altered thicknesses from the reference spring. Other than carbon fibers the dust from processing GRP material is not cancer causing.
But still it is not recommended to breath in the dust or have too much of it on the skin as it starts to itch really bad. Also breathing in GRP dust can cause Asthma or allergic reactions ([3],[4]).

### 3.1.5 Assembly of the spring

Now the springs are almost ready to use. A connection interface which allows us to connect the spring to the structure of the actuator needs to be included. In order to avoid generating large moments in the thinnest parts of the spring, a free rotating connection was implemented. Namely a small tube added to the tip of the spring legs fixed to the rest of the actuator with a bolt. The tube has a outer diameter of 4 mm and an inner diameter of 2.5 to 3 mm. Because the resin tends to resolve glue we fixed the tube with a strong thread.

Another problem is the difference in thickness between the spring leg and the tube. It is almost impossible to laminate GRP layers around the tube and not having a massive pocket of air beneath. To cope with that problem something to stuff the gap is required. In this case fine cotton balls were mixed into resin\(^2\). The more cotton the more pasty the mixture gets. With this material it is possible to level out the cap between the spring leg and the tube. Now it is no problem to laminate additional layers around the tube.

For that purpose we used a thinner (only 0.07 mm thickness) GRP fabric because it is more adaptive to round surfaces. In our first attempt we used nine additional layers with increasing length. So the last layer is again providing a smooth transition to the rest of the spring. The length of this additional layers is not very important. Their only function is to hold the copper tube on the tip of the spring legs. As the forces at the tips of the spring legs are not very high it is preferable to use as few material as possible. In our second build we slightly reduced the number of layers to eight. Figure 3.8 shows the springs after adding the connectors at the ends of the spring legs.

Finally the springs had to be cut at the end of the spring legs so they fit into the spring connectors of the structure of the actuator. This is illustrated with a CAD model in figure 3.9 on the left. Figure 3.9 on the right shows the CAD model of the spring mounted on the connector of the structure of the actuator.

\(2\)Same mixture as for the laminating itself
\(3\)small, 3 medium, 3 larger layer
\(4\)2 × 10mm, 2 × 8mm, 2 × 6mm, 2 × 4mm

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Figure 3.9: Left image: CAD model of the ready-to-use state of the GRP spring. Right image: CAD model of the spring mounted on the spring connector.
3.2 Non-linear spring

Since we were able to build a GRP leaf spring with a linear characteristic we extended our objective to non-linear springs with a progressive characteristic. A non-linear progressive spring would imitate the behavior of natural muscles much better since those have a non-linear characteristic as well.

3.2.1 Design idea

There is a variety of ideas how to make a structure stiffer the more force is applied. Most of them are based on sandwich constructions of different materials or thicknesses with different stiffness combined together in a way such that each element works on distinct interval of applied force. So it is possible to have a non-linear curve at the cost that it changes at certain points. As a huge drawback a spring design as described above would not have a continuous curve but several discrete steps.

We wanted to build a spring with continuous change in stiffness so we took advantage of a simple observation based on the material we used: Deformations of the GRP material lead to an increase in stiffness. Or in other words, the more the material bends, the stiffer it becomes.

In the U-shape the deformation was not enough since the two legs tend to touch in the middle. So we designed a spring which is able to deform more and therefore has a significant increase in stiffness the more force is applied. Of course this only works up to a certain maximum where the force gets too high for the structure of the spring and it breaks.

3.2.2 Computations

A detailed structural analysis is again out of the scope of this project. To get a easy result to start with we used the same assumptions and model we did in section 3.1.1 for the linear spring. Since we are interested in a high deformation we followed the computation of the linear 0.75 and 0.5 type of spring from the first and the second set of linear springs. We also designed a 1.0 type similar to the 1.0 linear spring type as a reference.

It is important to emphasize that all computations here were only ment to give some kind of guidance since the simple model we used for calculation does only apply well for small deformations which in our case is contradictory to the operation principle.

3.2.3 Counterblock

The form of the spring was guessed on a trial and error basis. For this purpose we tried to bend paper models, carton sheets and our other GRP springs. We then came up with a simple extended U shape in order to have a fast verification of the general principle our non-linear spring concept is based on. Figure 3.10 shows a photographs of the counterblock design. The back is longer so there is more room for the springs to deform. Also the opening angle of the spring legs is higher so the deformation is increased from the start. Downside of that fact is that the spring does not behave symmetrically in pushing and pulling situations. The counterblock itself is made the same way as our previous built described in section 3.1.2.
Chapter 3. Design of the spring

Figure 3.10: Photographs of the counterblock we used to build the non-linear GRP springs. Left image shows the front view and the right image is an isometric view on the whole counterblock.

3.2.4 Manufacturing of the spring

The general principle of the layer setup is the same as shown in figure 3.6 for the linear spring. Only difference was that thickest part of the spring was now extended over the whole back of the spring. Some additional layers on the back of the spring make sure that the assumption that this part is rigid part is still valid. The non-linear spring was made the same way as the linear spring, but with altered length of the layers. For detailed information regarding the layer setup please refer to appendix A. Figure 3.11 shows a photograph of one of the non-linear springs we built. In this picture the tubes we use as connectors at the end of the spring legs are already attached.

Figure 3.11: Non-linear GRP spring after cutting and grinding. The tubes at the ends of the spring legs are already attached.

There is an air pocket above the copper tube at the left tip of the spring leg. This air pocket reduces the stability of the spring connector but the connector is still strong enough not to break apart.
Chapter 4

Design of the Series Elastic Actuator

This chapter describes the process of designing the series elastic actuator which we used to test the grp springs in a hopping environment.

4.1 General Concept

Figure 4.1 illustrates the general concept of the previous actuator designs [1]. It works as follows:

- A motor drives a ball screw for linear motion.
- Three sliding parts (slider 1, slider 2, slider 3) are mounted on two parallel guides.
- A spring is connecting slider 1 and slider 2.
- The motor is connected to slider 3 while the ball screw nut is connected to slider 2.
- Slider 1 and slider 2 have a breaking mechanisms which allows them to hold their position on the guides independently.
- The leg of the robot is connected to the guides on one side and on slider 3 on the other side.

![Figure 4.1: Sketch of the general concept of the LMMA described in [1]](image)

This concept works well for the application of a knee joint of a walking robot developed at our lab. But we experienced problems with the breaking mechanism and the springs. For this project we decided not to care about the breaking but to find ways to cope with the spring problem. The improvement of the breaking mechanism is left for a future project. In our design we tried to provide an interface on which a breaking mechanism could be implemented later on without changing all the other parts of the actuator. Another simplification was that we fixed the position of slider 1.
A CAD model of the whole actuator is shown in figure 4.2. The operation principle is similar to the LMMA. The DC Motor on slider 3 drives the ball screw which is connected to slider 2. Slider 2 is then connected to slider 1 with a GRP leaf spring. There are no sensors mounted on the actuator but the hall sensor which is already installed in the DC Motor. For a proper control of the actuator at least linear potentiometer for the displacement have to be mounted. We suggest that the potentiometer would be installed between slider 3 and the guide.

![Figure 4.2: CAD model of the series elastic actuator with mounted GRP spring.](image)

### 4.2 Changes to previous designs

Because the overall goal is to make the whole actuator smaller we tried to miniaturize parts as long as their proper function was not negatively affected. For example the diameter of the ball screw was reduced from 6 mm to 4 mm since the smaller ball screw is still able to withstand occuring loads. Due to the smaller ball screw we were able to redesign the slider 2, so that the ball screw was more integrated into the structure. Figure 4.3 shows a CAD model of the new design of slider 2. This change reduces the required length of the ball screw and therefore the total length of the actuator. But there is still enough space for a breaking mechanism.

![Figure 4.3: Left image: isometric view on CAD model of slider 2. Right image: Top view on slider 2. The black bars are the guides. The yellow part is the ball screw. The ball screw nut is screwed into the structure of slider 2. On the left side of the slider is the spring connector.](image)
Since we use leaf springs instead of spiral springs we also had to design new connectors for the spring. Figure 4.4 on the left shows the new slider 1 design with the spring connector attached. In figure 4.4 on the right the spring is attached to slider 1. As mentioned before slider 1 is now fixed to the guides with small bolts on the sides.

We designed the connector as simple as possible but it is thinkable to change the design depending on the requirements of the GRP spring. It is important to mention that the connection of the spring needs to be either colinear with the guides or with an symmetric offset. Otherwise there is a resulting reaction force on the slider which could cause the slider to get stuck. With that in mind we can design a connector which can mount multiple springs. Refer to section 7.2 for additional informations regarding this topic.
Chapter 5

Evaluation

In this chapter we provide results from the spring tests we made. In section 5.1 the results from testing the first grp linear spring prototype are stated. In section 5.2 are the results from the first grp non-linear spring prototype and finally in section 5.3 are the performance measurements of the whole series elastic actuator when placed in the context of a hopping leg.

5.1 GRP linear spring test

For this kind of test we built a small test environment were we could mount the springs and apply weight $w$ (and therefore force due to gravitation) to them. Figure 5.1 shows a sketch of the test environment. The operation principle is the same as for the series elastic actuator. We used guides to prevent the spring to bend in direction perpendicular to the moving direction. For the force generation we used simple weights from dumbbells. With four 500 g and four 1.25 kg weights we could generate forces from 5 N to 70 N.

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{test_environment_sketch.png}
\caption{Conceptual sketch of the test environment we used for finding the spring characteristics. The displacement was measured with a potentiometer and read out manually with a multimeter. The results were then transfered into matlab manually.}
\end{figure}

The friction on the guides can be neglected as we are just interested in the static displacement at a given force. This force is acting on the leaf spring colinear to the direction of the gravitational force. We then measured the resistance $R$ between the two spring legs with a potentiometer. As the used linear potentiometer varies the resistance linearly the distance between the legs of the spring can be extracted with linear interpolation.
\[ d = d_{\text{min}} + \frac{d_{\text{max}} - d_{\text{min}}}{R_{\text{max}} - R_{\text{min}}} (R - R_{\text{min}}) \]

Where \( d \) is the distance measured with the potentiometer translated in millimeter. \( d_{\text{min}} \) in our case is 0 and \( d_{\text{max}} \) is the maximal length of the potentiometer in millimeter. \( R_{\text{min}} \) is the measured resistance at \( d_{\text{min}} \), \( R_{\text{max}} \) at \( d_{\text{max}} \) and \( R \) is the actual measured resistance. Reduced by the interpolated length of the spring without load \( d_0 \) that provides the displacement of the spring \( D \) at a given force level.

\[ D = d - d_0 \]

### 5.1.1 First prototype

Figure 5.2 to 5.4 show the force over the measured displacement diagram for the first prototype of our GRP leaf springs. Each data point indicates the average out of 5 independent measurements. The blue line indicates a quadratic fit of the measured data points. The 0.5 type of spring in figure 5.2 had only few data points, since small weights (less than 2 kg) already caused the spring to compress fully\(^1\). The graph looks non-linear progressive, but this is with a lot of uncertainty because of the few data amount. The other two springs in figure 5.3 and 5.4 also show non-linear characteristics. Namely progressive in figure 5.3 but also asymptotic in figure 5.4. This non-linearity is greatly influenced by the ripples the spring has in the outer surface layers.

\[ \text{Figure 5.2: Plot of applied force over measured displacement of the spring type 0.5. The blue line indicates a quadratic fit of the data points.} \]

\(^1\)Until the two spring legs touch.
5.1. GRP linear spring test

Figure 5.3: Plot of applied force over measured displacement of the spring type 1.0. The blue line indicates a quadratic fit of the data points.

Figure 5.4: Plot of applied force over measured displacement of the spring type 1.5. The blue line indicates a quadratic fit of the data points.

After a couple of test runs the 1.0 type of spring started to crack along a ripple in the outer surface layer. On figure 5.5 this crack is shown in the red circle. A crack reduces the stiffness of the spring drastically but the spring did not break apart. The characteristics of a broken spring are unpredictable but the spring is still safe and functional. This is an important aspect regarding the security of an actuator equipped with GRP springs.
Figure 5.5: Photograph of the GRP spring type 1.0. A crack in the structure (red circle) was developed after a couple of tests.

Since the test results of the first spring set was not very conclusive we decided to make another attempt to build the same springs again. The 0.5 type of spring was too soft and the 1.5 spring too stiff, therefore we changed this types to 0.75 and 1.25 respectively.

5.1.2 Second prototype

Figure 5.6 to 5.8 shows the force over measured displacement diagram for our second prototype of GRP leaf springs. Each data point indicates the average out of 5 independent measurements. The red line indicates a linear fit of the measured data points. Each plot shows almost perfect linear characteristics in the domain of force we applied. That fact shows us, that the surface of the spring is very important to their behaviour during stress. In figure 5.7 a non-linear increase of sampled characteristic curve is present at a high displacement. This can not be explained with the material properties as the plot for spring type 1.25 in figure 5.8 shows no such increase. So we suspect this increase to be due to measurement errors.

Figure 5.6: Plot of applied force over measured displacement of the spring type 0.75. The red line indicates a linear fit of the measured data points.

\[ \text{Thickness is 0.75 and 1.25 times the thickness we calculated with the online FEM tool, see section 3.1.3} \]
Figure 5.7: Plot of applied force over measured displacement of the spring type 1.0. The red line indicates a linear fit of the measured data points.

Figure 5.8: Plot of applied force over measured displacement of the spring type 1.25. The red line indicates a linear fit of the measured data points.

**Spring constant**

With a linear spring characteristic curve it is possible to compute the spring constant using Hooke’s Law. Figure 5.9 shows the result of the computation of the spring constant for each sample point (crosses in the previous graphs):

\[ k_i = \frac{F_i}{x_i} \]

where \( F_i \) is the applied force and \( x_i \) the average of the measured displacements of sample point \( i \).
The spring constant is more or less constant (only a small change in magnitude) for all spring types. All the springs show a light increase in stiffness the higher the forces and therefore the higher the deformation becomes. The material increases the stiffness as a reaction to the deformation up to a certain level at which the structure starts to delaminate and the spring eventually breaks. This observation led to the development of the non-linear spring. We try to take advantage of this fact by increasing the deformation. For the three spring types we built, the average of the spring constant is:

- Type 0.75: 1.27 N/mm
- Type 1.0: 2.04 N/mm
- Type 1.25: 2.62 N/mm

The spring constant of the steel spring which was used in [1] was 2.27 N/mm. This shows that we are in the same range.

5.2 GRP non-linear spring test

We placed the non-linear spring in the same experimental environment and applied force the same way we did for the linear spring. Figure 5.10 to 5.12 show the force over measured displacement for all non-linear spring types. In all plots we can see the almost linear characteristic until the deformation gets high enough such that the stiffness increases drastically. In figure 5.12 we don’t see the non-linear increase in stiffness. This is because the applied force of 70 N was not high enough to deform the spring to the non-linear area of operation.

This results demonstrate that it is possible to design GRP springs with non-linear progressive stiffness only by the design of the shape of the spring and not with the combination of different shapes or materials.
5.2. GRP non-linear spring test

Figure 5.10: Plot of applied force over measured displacement of the spring type 0.5. The violet line indicates a cubic fit of the measured data points.

Figure 5.11: Plot of applied force over measured displacement of the spring type 0.75. The violet line indicates a cubic fit of the measured data points.
Chapter 5. Evaluation

Figure 5.12: Plot of applied force over measured displacement of the spring type 1.0. The violet line indicates a cubic fit of the measured data points.

Spring parameter

In the case of the non-linear spring characteristic we can no longer have a constant parameter for the spring. The spring parameter changes with respect to the displacement. Therefore $k$ is now a function of $x$.

$$F(x) = k(x) \cdot x \rightarrow k(x) = F(x)/x$$

Figure 5.13 shows the distribution of the spring parameter we computed for each sample point (crosses from the previous graphs). For the 0.5 and the 0.75 type there is a significant increase of the spring parameter at higher forces. This increase corresponds to the increase in stiffness of the spring. For the 1.0 type of spring we see a constant distribution. This also corresponds to the linear characteristic we observed in that range of forces.

Figure 5.13: Plot of the spring parameter distribution for each spring type. The green line corresponds to the 1.0 type, the blue to the 0.75 type and the red to the 0.5 type of spring.
The ranges of the spring parameter for the three types of non-linear spring we built is:

- Type 0.5: 0.2...0.4 $N/mm$
- Type 0.75: 0.4...0.8 $N/mm$
- Type 1.0: 1...1.2 $N/mm$

The stiffness of all three springs is low. A low stiffness corresponds to a high displacement. A high displacement corresponds to a high deformation. So the increase in stiffness is higher for springs with a lower stiffness. But the higher the forces on a soft spring the closer the strain gets to the point where the spring breaks. The solution to this trade-off depends on the application in which the spring is acting.

### 5.3 The hopping experiment

After developing both the springs and the series elastic actuator we placed all parts together to see how they perform in a hopping experiment. The mathematical modelling and related calculations are shown in appendix A.2. We have two possibilities how we can achieve hopping. The loaded spring and the excited spring hopping.

**Loaded spring**

Since we have a series elastic actuator we can not load the spring because that would require a breaking mechanism in the slider connected to the spring. Figure 5.14 shows an illustration how the jump was made. We tried to achieve jumping by fixing the motor and manually loading the spring by pressing down the slider. After releasing the slider the whole series elastic actuator jumps couple of centimeters.

![Figure 5.14: CAD illustration of the series elastic actuator generating the jump. The red arrow represents the manual pushing of the slider. The compression of the spring (green arrow) causes the jump (blue arrow) after releasing the slider.](image)

Table 5.3 shows the result from few samples. The jumping hight ist depending on the displacement of the spring. In each test run we tried to load the spring to its maximum in order to get the maximum jumping hight.
Table 5.1: Jump test results with various manually loaded springs.

<table>
<thead>
<tr>
<th>Spring type</th>
<th>displacement [mm]</th>
<th>jumping height [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>non-linear 0.75</td>
<td>80</td>
<td>90</td>
</tr>
<tr>
<td>linear 0.75</td>
<td>50</td>
<td>60</td>
</tr>
<tr>
<td>linear 1.0</td>
<td>30</td>
<td>40</td>
</tr>
</tbody>
</table>

The resulting jumping height of all tested springs was larger than the displacement. This simple test illustrates how much energy can be stored in GRP leaf springs.

**Excited spring**

The other approach was to initiate hopping by exciting the spring. Figure 5.15 illustrates how the spring can be excited. By driving the ball screw in a sinusoidal movement, the DC motor causes the spring to compress and release. At a certain frequency, the natural frequency of the damped oscillator, the whole actuator starts to hop.

![Figure 5.15: CAD illustration of the series elastic actuator generating the hopping movement. The up- and downward movement (red arrows) initiate a compression and release of the spring (green arrow). At peak frequency the actuator starts to hop.](image)

Unfortunately we did not succeed in achieving significant hopping heights. For all spring types we tried driving the motor around the natural frequency since the exact natural frequency is hard to estimate. Also we tried different loads\(^3\) on the actuator. This was not enough to cause the actuator to hop. Only vibrations in the structure of the actuator were visible.

We suspect the friction in the actuator and the internal damping of the spring to cause the natural frequency to be smeared over many frequencies. Hopping is not possible if the resonant peak of the swinging spring is not high enough.

Figure 5.16 shows the amplitude gain response of the linear 0.75 type of spring with a load of 3.75 kg. The higher the single resonant peak the higher the actuator is able to

---

\(^3\)0.5 kg to 3.75 kg
hop. In our case the highest peak at around $31 \text{ rad/s}$ was not high enough to lift off the ground. Also other smaller peaks indicate that there is no unique natural frequency.

Figure 5.16: Amplitude response gain of the excited GRP leaf spring type 0.75 with 3.75 kg load.

In order to get better results additional tests on this topic have to be made in the future.
Chapter 6

Conclusion

We showed in this project that it is possible to design GRP springs with a linear characteristic. The spring constant of such a spring is comparable to spiral steel springs but with the benefit of a lower weight\(^1\) and a much simpler assembly of the actuator. During our work on the project we also discovered that a non-linear progressive spring characteristic can be achieved without using patchwork or sandwich techniques. By using the basic fact that the material gets stiffer the more it deforms we designed a spring which has a continuous non-linear characteristic. This is an interesting discovery for the design of bio-inspired robots because natural muscle also have a non-linear progressive spring behavior.

In the hopping experiment we showed that the storable energy in GRP leaf springs is very high. This allows us to build very efficient walking and jumping robots. We also discovered a very high damping property of our spring design. As a drawback this damping makes excited spring hopping very difficult. But there is also an upside. High internal damping is preferable for shock absorbance, e.g. after a jump over an obstacle. With internal dampers we can take out energy of an impact without having to insert additional damping elements. This makes robot structures lighter and also more resistant to shocks of impacts.

The cost of GRP material is very low compared to other composite materials, but also to steel and aluminium. The big problem here is the manufacturing. Since we still depend on hand-made GRP structures the manufacturing process is expensive and very error-prone. With an automated lamination process that would be solved, but up to now such equipment is very expensive. Until this problem is addressed, GRP spring are unlikely to endanger the dominance of steel springs. Especially with regard to mass production. With this project we showed that GRP material has a high potential to replace standard metallic elements in order to get closer to our biological role models. Therefore for bio-inspired robotics composite spring development may gain importance. But still a lot of research is required to efficiently impose their use in modern robotics in general.

\(^1\)Weight of GRP springs is around 30 g compared to 90 g of the comparable steel spring.
Chapter 7

Future work

Although we found designs of GRP leaf springs which have linear as well as non-linear progressive characteristic, we are not yet at the point where we can replace all steel springs by GRP springs. In the following several points are mentioned where we need to do more research before our idea becomes practical.

7.1 Work on the spring

In this section several suggestions regarding the spring design are stated.

Spring design

We only investigated the U shape form of spring. But since almost every shape is possible, there is maybe a better solution. Also the combination of CF and GRP could be interesting to investigate, especially for stiffer springs with higher target forces.

Linear spring

The manufacturing of the spring was very time consuming and required multiple steps with 24 hours waiting time in between. Probably there are ways to simplify that process. Especially the mounting of the connector tubes could probably be integrated in the production of the spring itself. This would save a third of the production time.

Non-linear spring

The design of the non-linear spring is very simple and came straight forward from the development of the linear spring. Since the whole idea of the non-linear spring is to increase the deformation while compressing the spring, there could be other shapes how to achieve that. The trade-off mentioned in section 5.2 also needs to be investigated further.

7.2 Work on the actuator

In this section we mention points where future work on the actuator could be done.

Break mechanism

The break mechanism is not implemented in the series elastic actuator presented in this project. But since the overall goal is to build a multi mode linear actuator, a breaking
mechanism is required. The breaks should be able to fix the sliders on the guides. In all previous prototypes this break mechanism was based on friction. By applying pressure the break shoe is pressing on the guides. This increases the friction. The slider is fixed once the friction of the breaks is higher than the force acting on the slider.

Another important advantage of the friction based breaks is that it is independent from the position on the guides. With a form-closed approach this is not necessarily the case. In [1] a mechanism with an ellipse which presses two break shoes symmetrically on the guides is proposed. One challenge could be to increase the friction on the break shoe. Figure 7.1 shows a sketch how this could be achieved using cam belts both on the guide and on the break shoe. The bigger the teeth of the belt the closer it gets to a form-closed approach. A good trade-off is key.

![Figure 7.1: Conceptual sketch of the belt idea.](image)

Multiple springs

The effective spring constant can also be changed by adding more springs in parallel. Figure 7.2 shows a sketch of two parallel springs. The resulting spring constant $k_{tot}$ of parallel springs is

$$k_{tot} = k_1 + k_2$$

with $k_1$ the constant of the first and $k_2$ the constant of the second parallel spring.

![Figure 7.2: Two springs in parallel can be simplified to one.](image)

this can be used to change the effective spring constant of the actuator. A conceptual CAD model of the actuator with two mounted springs is shown in figure 7.3.
Figure 7.3: SEA with two springs mounted in parallel.

It is important to have a symmetric design of the spring connector because the reaction force on the spring connector needs to be colinear with the moving direction. Otherwise the slider experiences turning moments and can get stuck. Figure 7.4 shows a possible connector with two springs mounted symmetrically.

Figure 7.4: Left image: CAD model of spring connector with two GRP springs mounted symmetrically. Right image: Detail view on the spring connector.
Appendix A

Calculations

A.1 Linear and non-linear springs

For the calculations we assumed isotropic material conditions based on the crossbred fabric. Figure A.1 shows a screenshot of the excel table we used to do some basic calculations. This was a very iterative process.

**Inertia**

The width \( w \) of the spring we set to 30\( mm \). The thickness \( d \) of the back of the spring we assumed to be 3.1\( mm \). Therefore for the inertia we have

\[
I_{\text{back}} = \frac{w \cdot d^3}{12} = 74.8 \text{mm}^4
\]

**E-modulus**

We started from the E-modulus value we found in [2] for glass fibers. The crossbred fabric (which has the same amount of fibers in horizontal and vertical direction) which we used, in practice is only able to use half of the fibers for stability. Therefore we divided the modulus by two. Since almost half of the volume of the spring is resin, we divided the modulus again by two. So

\[
E = \frac{86000}{4} = 21500 \frac{N}{mm^2}
\]

**EI value**

The EI value which we used to determine the shape of the bar in the online FEM tool was then

\[
E \cdot I_{\text{back}} = 1601266.25 Nmm^2
\]

for the back of the spring. The analogue calculation (thickness \( d = 0.9mm \)) leads to the EI value of the second segment, the tip of the spring leg:

\[
E \cdot I_{\text{tip}} = 39183.75 Nmm^2
\]
Strain distribution

A force \( f \) of 100N attacks at the end of the spring legs. Since the spring legs have a length \( l \) of 70 mm, this leads to a bending moment of \( M_b = f \cdot l = 7000 \text{Nmm} \). Since the thickness is changing linearly over the structure of the spring and with the resistance moment for each segment

\[
I_{w\text{back}} = \frac{w \cdot d^2}{6}
\]

we can compute the strain distribution over the whole spring leg. The strain at the back of the spring is therefore

\[
\sigma_{\text{back}} = \frac{M_b}{I_{w\text{back}}} = 145.68 \frac{N}{\text{mm}^2}
\]

This value is lower than the critical strain. In our case that is true for each segment of the spring.

Figure A.2 show a screenshot of the same considerations for the non-linear spring.

A.2 The hopping experiment

For the hopping experiment we used basic calculations similar to [5]

Mathematical model

The simplified mathematical model of the experiment is shown in figure A.3. The total mass acting on the slider is denoted as \( m \). This is the combined mass of the structure and the additional load. The spring constant is denoted as \( k \) and \( d \) is the internal damping of the spring combined with the influence of friction on the sliders. The displacement of the load is \( x \). This is also the state variable of the system.

\[
\begin{align*}
g & \\
m & \\
d & \\
k & \\
x & \\
\end{align*}
\]

Figure A.3: Simplified mathematical model of the jump environment

The equation of motion for a mechanical system like this is

\[
m \cdot \ddot{x} + d \cdot \dot{x} + k \cdot x = 0
\]

Normalized by the mass \( m \) this equation becomes

\[
\ddot{x} + \frac{d}{m} \cdot \dot{x} + \frac{k}{m} \cdot x = 0
\]

Since this is the equation of a damped oscillator, we see the resonance frequency \( \omega_0 \) of the spring is given by

\[
\omega_0 = \sqrt{\frac{k}{m}}
\]
The damping ratio $\zeta$ can then be calculated using

$$\zeta = \frac{d}{2 \cdot m \cdot \omega_0}$$

The problem here is, that the damping of the spring $d$ is hard to estimate. One way how to achieve that is by analysing the swing behavior of the spring. For that purpose we need to measure an initial displacement $x_1$ and the displacement after one full swing cycle $x_2$. With this two values we know how much movement the spring absorbed. This corresponds to the damping which can be calculated using

$$d = \ln \left| \frac{x_1}{x_2} \right|$$

The damped natural frequency $\omega_d$ can then be computed using

$$\omega_d = \omega_0 \cdot \sqrt{1 - \zeta^2}$$
Figure A.1: Excel sheet used to predict the required thickness of the spring.

<table>
<thead>
<tr>
<th>Thickness</th>
<th>X-Value</th>
<th>Y-Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.15mm</td>
<td>0.125cm</td>
<td>2.0mm</td>
</tr>
<tr>
<td>0.15mm</td>
<td>0.125cm</td>
<td>2.2mm</td>
</tr>
<tr>
<td>0.15mm</td>
<td>0.125cm</td>
<td>2.4mm</td>
</tr>
<tr>
<td>0.15mm</td>
<td>0.125cm</td>
<td>2.6mm</td>
</tr>
<tr>
<td>0.15mm</td>
<td>0.125cm</td>
<td>2.8mm</td>
</tr>
<tr>
<td>0.15mm</td>
<td>0.125cm</td>
<td>3.0mm</td>
</tr>
<tr>
<td>0.15mm</td>
<td>0.125cm</td>
<td>3.2mm</td>
</tr>
<tr>
<td>0.15mm</td>
<td>0.125cm</td>
<td>3.4mm</td>
</tr>
<tr>
<td>0.15mm</td>
<td>0.125cm</td>
<td>3.6mm</td>
</tr>
<tr>
<td>0.15mm</td>
<td>0.125cm</td>
<td>3.8mm</td>
</tr>
</tbody>
</table>

Note: The Excel sheet includes additional calculations and data points not shown in the table.
### A.2. The hopping experiment

Figure A.2: Excel sheet used to predict the required thickness of the spring

<table>
<thead>
<tr>
<th>Hole Diameter (mm)</th>
<th>0</th>
<th>10</th>
<th>15</th>
<th>20</th>
<th>25</th>
<th>30</th>
<th>35</th>
<th>40</th>
<th>45</th>
<th>50</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thickness (mm)</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
</tr>
</tbody>
</table>

The table above shows the predicted required thickness of the spring for various hole diameters. The thickness is calculated based on the spring's material properties and the required force for hopping.
## Appendix B

### Ordered Parts

**Legend**
- Suter Kunstroffe AG (SK): http://www.swiss-composite.ch
- Maedler GmbH (M): http://www.maedler.ch
- Maxon Motors (MM): http://www.maxonmotor.ch
- igus Bearings (IG): http://www.igus.ch
- Coop Bau und Hobby (CBH): http://www.coop.ch/bauundhobby

### Part list

<table>
<thead>
<tr>
<th>Part Desc.</th>
<th>Order nr.</th>
<th>Amount</th>
<th>Dealer</th>
<th>Price [CHF]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ball screw</td>
<td>SRT0401-147R187Cr0BmX</td>
<td>2</td>
<td>KSS</td>
<td>665</td>
</tr>
<tr>
<td>DC Motor + Encoder</td>
<td>333437</td>
<td>1</td>
<td>MM</td>
<td>356</td>
</tr>
<tr>
<td>EPOS2</td>
<td>3900003</td>
<td>1</td>
<td>MM</td>
<td>395</td>
</tr>
<tr>
<td>GRP fabric 163g/qm</td>
<td>190.1158</td>
<td>5m</td>
<td>SK</td>
<td>82</td>
</tr>
<tr>
<td>GRP fabric 81g/qm</td>
<td>190.0070</td>
<td>2m</td>
<td>SK</td>
<td>0</td>
</tr>
<tr>
<td>Torn away fabric 85g/qm</td>
<td>190.1100</td>
<td>2m</td>
<td>SK</td>
<td>0</td>
</tr>
<tr>
<td>Epoxy L resin, work package</td>
<td>100.1101</td>
<td>1 kg</td>
<td>SK</td>
<td>0</td>
</tr>
<tr>
<td>igus bearing</td>
<td>JSM-1012-05</td>
<td>26</td>
<td>IG</td>
<td>40</td>
</tr>
<tr>
<td>Ball bearing</td>
<td>624.2Z-SKF</td>
<td>5</td>
<td>M</td>
<td>92</td>
</tr>
<tr>
<td>coupling steel</td>
<td>60299602</td>
<td>2</td>
<td>M</td>
<td>44</td>
</tr>
<tr>
<td>MDF wood</td>
<td>N/A</td>
<td>2x(22x10x100)</td>
<td>CBH</td>
<td>6</td>
</tr>
<tr>
<td>tape</td>
<td>N/A</td>
<td>1</td>
<td>CBH</td>
<td>6</td>
</tr>
<tr>
<td>cling film</td>
<td>N/A</td>
<td>1</td>
<td>CBH</td>
<td>3</td>
</tr>
<tr>
<td>alu tubes</td>
<td>N/A</td>
<td>1x1m</td>
<td>CBH</td>
<td>4</td>
</tr>
<tr>
<td>copper tubes</td>
<td>N/A</td>
<td>1x1m</td>
<td>CBH</td>
<td>4</td>
</tr>
<tr>
<td>thread</td>
<td>N/A</td>
<td>1</td>
<td>CBH</td>
<td>5</td>
</tr>
</tbody>
</table>

*Figure B.1: List of ordered parts with the ordering number and approx. prices*
Appendix C

Contact Persons

Workshop

- Pascal Wespe: Material ordering and manufacturing of parts
  E-Mail: pascal.wespe@mavt.ethz.ch

- Alessandro Rotta: Manufacturing of milled parts
  E-Mail: rotta@mavt.ethz.ch

Composite Lab

- Thomas Heinrich: Responsible for the composite lab
  E-Mail: thomas.heinrich@imes.mavt.ethz.ch

- Markus Zogg
  E-Mail: zogg@inspire.ethz.ch

KSS Ballscrew

- Martina Nava from GARNET s.r.l
  E-Mail: martina.nava@garnetitalia.com
Appendix D

Step-by-step Instruction

This chapter is a step-by-step instruction of how to make GRP springs as described in this report.

D.1 Preparation

D.1.1 Counterblock
1. Build counterblock (CB)
2. Seal CB with tape
3. Mark middle line and position of springs on CB

D.1.2 Layer
1. Cut layers from fabric according to layer setup for all springs (refer to A.1).
2. Mark the center of the layer.
3. Order layers according to their symmetric setup: first layer is on the inside later on, last layer is the outer layer (see figure 3.6 in section 3.1.3).
4. Prepare torn away fabric:
   • One torn away fabric on the inside, one on the outside of each spring leg.
   • Torn away fabric allows us to laminate further layers later on (rough surface) which we need for the small tube connectors.

D.1.3 Resin
1. Make sure the room is supplied with fresh air.
2. Mix resin according to the mix ratio (resin to hardener)
   • Volume: 100 to 45
   • Mass: 100 to 40
3. Mix thoroughly for approx. 1 min with a wooden stick

Note: Resin-Hardener mixture will start to get hard in 45 min! If the mixture becomes hot, the mix ratio was wrong.
D.2 Lamination

Security Notes

- The resin is irritating, make sure to wear gloves at any time.
- Always make sure that fresh air can enter the room.
- Resin on clothes will stay and can not be washed out!

Procedure

1. Apply small film of resin on counterblock with a brush.
2. Place torn away fabric at the future spring legs.
3. Repeat until all layers are laminated:
   - Apply resin on the previous layer with the brush (the less the better, but enough to saturate the previous layer. A darker layer indicates that it has resin soaked in. Make sure you apply resin by dabing and not by coating to avoid shifting the layers.)
   - Place next layer with the center mark aligned with the center line of the CB.
4. Place torn away fabric on the outer layer.

Note: If air pockets occur (paler points), try to work them out by dabing on them with the brush.

D.3 Vacuum

The following steps are not required, but we recommend to use a vacuum bag in order to press the layer together, get rid of redundant resin and reduce the amount of air pockets.

1. Place perforated plastic foil around the spring.
2. Place filter film around the spring.
3. Place package into vacuum bag (VB).
4. Insert valve into the VB.
5. Seal the VB airtight.
6. Connect the vacuum pump and start it slowly.
7. The VB will contract. Four hours in the VB are enough.
8. Make sure to shut down the vacuum pump!
9. Remove the VB and put away the package for at least 24 hours before you remove the filter film and the perforated foil.

Note: If ripples occur in the outer layers, additionally place torn away fabric all the way on the outer surface of the spring before placing in the VB.
D.4 Spring connectors

Preparation
1. Mark where the springs are on the outer layer.
2. Remove the springs from the counterblock.
3. Cut the springs along the markings (we suggest you use a Dremel).
4. Grind the spring if not even.
5. Cut pieces from the copper tube (or any other small tube you have for the connector) with the same length as the width of the spring. Two pieces for each spring.
6. Remove the torn away fabric from the spring legs (inside and outside).

D.4.1 Pre-steps
1. Glue one tube at the tip of each spring leg.
2. Tie the tubes with a strong thread on the spring leg (as the resin tends to resolve the glue).
3. Prepare the spatula (mix resin-hardener mixture as for the lamination process but add cotton balls until mixture gets pasty).
4. Clean the spring legs using acetone.
5. Even out the gap between the tube and the spring leg with the spatula.
6. Let the spatula harden out for at least four hours.

D.4.2 Lamination
Preparation
1. Prepare additional layers (thinner fabric):
   - For example: 2 x 2cm, 2x 4cm, 2x 6cm, 2x 8cm for each spring leg

Procedure
1. Laminate as described in D.2.
2. Put in VB as described in D.3

D.4.3 Cutting
1. Grind the sides of the springs until they are even.
2. Mark the place which needs to be cut out according to the spring connector.
3. Roughly cut and then grind using a file until the spring fits into the connector.
Appendix E

Technical drawings
Guide
Aluminium, 2 pieces
Bryan Anastasiades, 5.6.2011
Guide Connector
Aluminium, 2 pieces

Bryan Anastasiades, 5.6.2011

ALL DIMENSIONS IN MM

3D CAD MASTER PART NAME:
Spring Connector
Aluminium, 3 pieces
Scale 2:1
Bryan Anastasiades, 5.6.2011
Motor block
Aluminium, 2 pieces

Bryan Anastasiades, 5.6.2011
Spring Slider
Aluminium, 2 pieces
Bryan Anastasiades, 5.6.2011
Simple Guide Connector
Aluminium, 3 pieces

Bryan Anastasiades, 5.6.2011

ALL DIMENSIONS IN MM
3D CAD MASTER PART NAME:
SRT0401-147R1B7C10BOX
Standardized Rolled Ballscrew
Diameter 4mm
Lead 1mm
Thread Length 147mm
Thread Direction Right Hand
Screw Shaft Total Length 187mm
Accuracy Grade C10
Shaft End Journal Profile B
KSS Grease
Nut Flange Direction X

3D CAD MASTER PART NAME:  ALL DIMENSIONS IN MM
Bibliography


   http://de.wikipedia.org/wiki/Glasfaserverstarkter_Kunststoff


   http://en.wikipedia.org/wiki/Harmonic_oscillator