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Mechanical Engineering and Production Technology

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Concept design of composite axis for Cencorp high-speed odd-form component placing machine

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Abstract

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The purpose of this thesis was to study the possibilities of creating a lighter design of an axis system for a new high-speed odd-form component placing machine. The mass reduction possibilities were mainly studied by changing the material to a lightweight composite material but also structural design aspects were considered. The end goal of this study was not to reach a complete new design but rather find out if it is possible to build the axis system from a composite material so that it fulfils the needed requirements while still being economically and practically reasonable. Systematic product development strategies were used to clarify the practical requirements of the new axis system. The work was commissioned by Cencorp Automation Oy.

Data for this study was gathered from literature, internet sources and persons with knowledge of either Cencorp machines or composite manufacturing and design. Practical data of the possible materials and their properties was gathered in collaboration with a company called CSI-Composites Oy.

The result of this study shows three different concepts of the new axis, a static FE-analysis of each including maximum displacements and stresses. The study also includes a description of a systematic product development process and theory for designing composite parts.

Keywords: composite, carbon fiber, structural design, FE-analysis, systematic product development

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Terminology, concepts and symbols

OF – Odd-form component placing machine

PCB – Printed circuit board

SMT – Surface Mount Technology

SMD – Surface Mount Device

THT – Through-Hole Technology

RTM – Resin Transfer Molding

FEM – Finite Element Method

X-direction – along the width of the machine (see Figure 2)

Y-direction – along the length of the machine (see Figure 2)

Z-direction – along the height of the machine (see Figure 2)

σ = Stress

ε = Strain

E = Young's modulus

A = Area

m = Mass

a = Acceleration

τ = Shear stress

1 Introduction

For decades, the industrial processes were carried out by hand. From sawing wood to welding and PCB assembling, everything has required a real person to do the work. The technological development and the development of the markets have, however, changed this tradition of industrial processes. Components and products need to be manufactured more cost- and time-effectively, more precisely and in larger volumes in order for the company to succeed in the competition. In many companies, this has led to automatization of the processes and replacing the labor with machines.

The same requirements as listed above apply also for the machines that are replacing the humans in the production lines. Especially the lead times are crucial; the number of products produced in a certain amount of time is almost directly proportional to the profits and payback time of the machine investment. This means that the automation machine with shorter lead times is more appealing and has more market value than the competitor with the same price.

Due to the reasons mentioned above, Cencorp Automation Oy commissioned this thesis to be the first step of a project in which a new high-speed odd-form component placing machine is the end goal. The increased acceleration of the axis can be reached by either lowering the mass of the axis or by increasing the power of the motors. Increasing the power would, however, require a liquid cooling system for the motors. Mass reduction was chosen to be the method of reaching the wanted accelerations. This thesis investigates the possible solutions to reach the lightened structure while maintaining the required mechanical properties.

The biggest task is to build preliminary models of the new axis that can then be analysed with calculations and finite element method. A lot of fundamental information about composites and composite designing needs to be gathered before the analysis can be made.

2 Cencorp Automation Oy

Cencorp Automation Oy, later referred to only as Cencorp, is one of the world's leading process automation providers. Cencorp products range from PCB depaneling and odd-form component placement to laser welding and -marking, final assembly and test handling. The innovative automation solutions significantly increase the efficiency of customers' production processes. Cencorp customers include for example the leading companies in automotive electronics, telecommunications and industrial electronics. (Cencorp, A)

Cencorp headquarters is located in Salo, Finland. In the end of 2017, the headquarters moved to new premises located in the campus that used to be the head office of Nokia. Nowadays the campus carries the name Salo IoT Campus. In addition to production plants in Salo and China, Cencorp has regional sales and service facilities in North America, China and Europe with more than 150 employees in total. Cencorp's global network of sales representatives and distributors cover all the major markets of the world. Cencorp Automation Oy had 13,5M€ revenue in 2016. (Cencorp, A)

2.1.1 History

The history of the company dates back to 1948 when a Finnish electronics company Evox Ltd was founded. Cencorp Automation Oy slowly started to grow on this foundation. The first assembly cell for odd-form components was built in 1986. The current name of the company originates from Colorado Engineering Corporation, a company that was acquired by PMJ Automec Corporation in 1999.

In 2014, after eventful years with many ups and downs, a Chinese private equity company FTTK Company Limited acquired Cencorp. Cencorp Automation Oy, as we know it today, was established and with heavy investments in facilities and organization the company is now on the way of steady growth. (Cencorp, B)

2.2 Odd-form placement

Printed circuit boards (PCBs) are nowadays the foundation of almost every, partly or completely, electronic product. The main task of the PCB is to work as a mechanically supportive platform and at the same time electrically connect the components that are placed on the board. Since one PCB can connect a lot of components, assembling the PCB is a critical phase when it comes to efficiency and profitability of the process. Assembling of the PCB is traditionally made by hand. However, mass production and high demand have created a market for automated PCB assembling machines, such as pick-and-place component placement machines. The term “odd-form” means that the components can be different in shapes and sizes. There are two widely used methods of placing the components on the PCB.

- SMT – Surface Mount Technology
    - The components are placed on the surface of the PCB and then soldered. Components leads do not go through PCB and this allows easier automation of the process and use of smaller components. Normal SMT components are for example transistors and diodes, integrated circuits and passive surface mount devices (SMD’s) such as resistors and capacitors. (Electronics notes, n.d.)

- THT - Through-Hole Technology
    - Through-hole components have long leads, also known as “legs”, that are placed through holes that are drilled in the PCB and then fixed in place by either soldering or clinching the leads. Component legs can be radial or axial. Even though SMT technology has widely replaced through-hole technology, it is still used for example with large, mechanically stressed, high voltage or high power components. (AER Technologies)

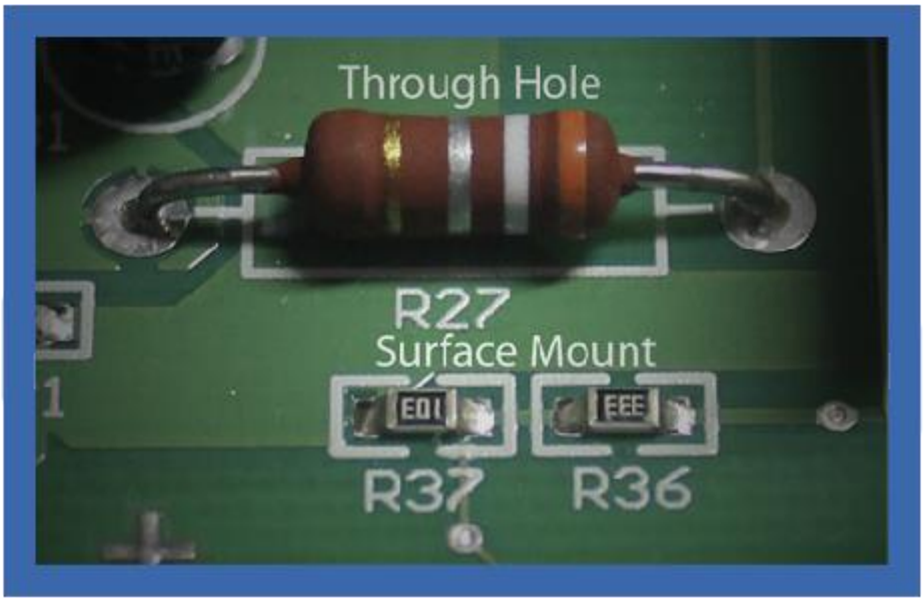


Figure 1 Through-Hole vs. Surface Mount Technology (AER Technologies)

2.3 Cencorp Odd-form placement machines

In the spring of 2018, Cencorp product portfolio includes three different odd-form placement machines. Each one of them is designed for through-hole component placement in high volume and high mix production. (Cencorp, C)

- **1500 OF** is designed for maximum feeder capacity and excellent placement quality. The latest linear guide technology and active clinching unit ensure the quality of every component placed. The main dimensions are 1485 mm x 1838 mm x 1669 mm. (Width, height, depth)
- **1000 OF EVO**'s upgraded control system and user interface, active clinching unit and flexible feeder capacity make it a reliable choice for replacing manual work processes. The main dimension are 990 mm x 1744 mm x 1560 mm.
- **850 OF** is a slim and affordable choice for process automation. Fast and flexible pick-and-place robot combined with product specific support fixtures are keys to high quality process. The main dimension 865 mm x 1724 mm x 1558 mm.

Figure 2 Cencorp 1000 OF EVO and the coordinate system used at Cencorp (Cencorp, C)

3 Composites

Composite is a universal name for a material made of two or more different materials and in which the materials work together without being dissolved or merged together. The most common composites nowadays are reinforced concrete, reinforced plastics and different kind of wood composites, such as plywood. Reinforced plastics play the biggest role in the field of mechanical engineering because of their unique properties and the rising need of building lighter and smaller machine parts. In most of the composites, one of the materials can be held as the bonding material that "glues" the other materials together. This material is called matrix. Matrix itself can also be a combination of many materials, meaning that it can be a composite even before the reinforcements are added. (Saarela, Airasmaa, Kokko, Skrifvars, Komppa, 2003)

The development of composites started in the beginning of the19th century when the first patent for reinforced plastic was granted. The first customers for composite products were aerospace and marine industry. These industries are still one of the biggest users of composites with automotive and transport industry, which is the most rapidly rising composite user. However, composites have proven to be a noteworthy alternative for steels and other metals also in other fields of technology too. High strength-to-weight -ratio, stiffness and possibility to control the mechanical properties are the main advantages of composites when comparing to metallic materials. (Saarela et al. 2003)

In this thesis, mostly reinforced plastic composites are dealt with. More specifically carbon fibre reinforced polymers and their properties, manufacturing aspects and designs. Even though there are many other equally appealing engineering composites available, carbon fibre was chosen as the material for this study due to the availability of manufacturers and its well-known properties.

3.1 Manufacturing techniques

Manufacturing of plastic composites has developed a lot since the early stages of composites and nowadays there are multiple manufacturing techniques in use. Techniques can be roughly divided into two main categories: manufacturing by

hand and manufacturing by machine. More commonly, the division is made according to the methods of creating the desired shape and design. The division and some examples are shown below. (Saarela et al. 2003)

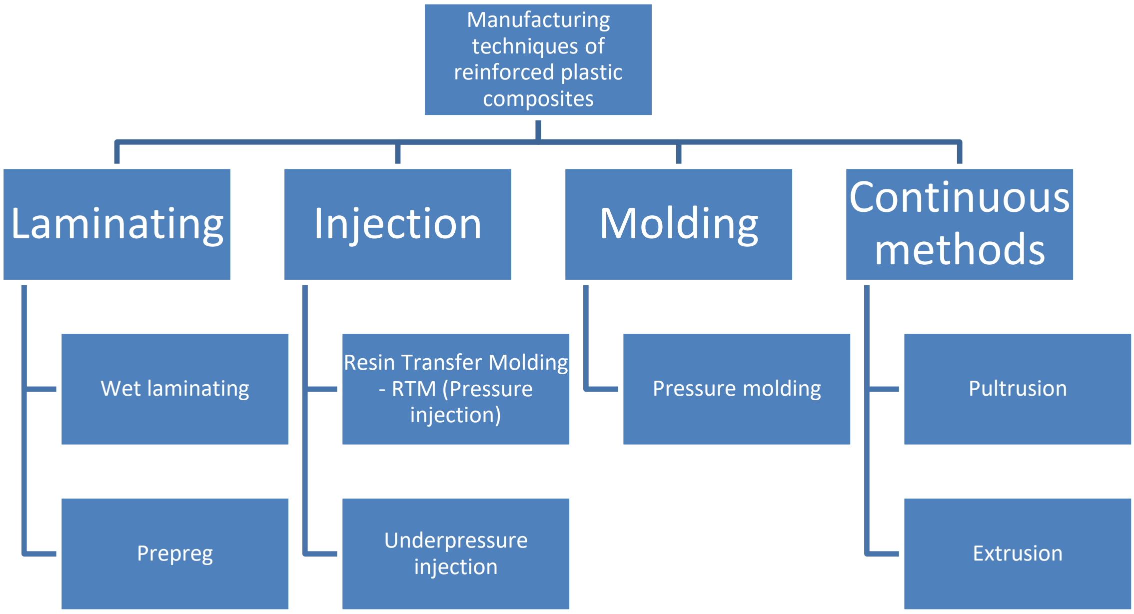


Figure 3 Reinforced plastic composite manufacturing techniques (Saarela et al. 2003).

3.2 Designing composite structures

Designing of composite structures differs from traditional metal structure design significantly. The anisotropic nature of fibre-reinforced composites creates both possibilities and challenges. Anisotropy means that the material has different properties in different directions whereas for example steel behaves equally in all directions. The anisotropy of composites gives the possibility to manipulate the directional properties, such as stiffness. The manipulation can be made for example by changing the layout and orientation of fibre filaments, changing the continuity of the filaments or by fibre interlocking. By doing this, the behavior of the final product can change dramatically, since the filaments behave completely differently in axial and radial directions. The tensile properties of the fibres are the ones that reinforce the structure. (Mallick, 2008)

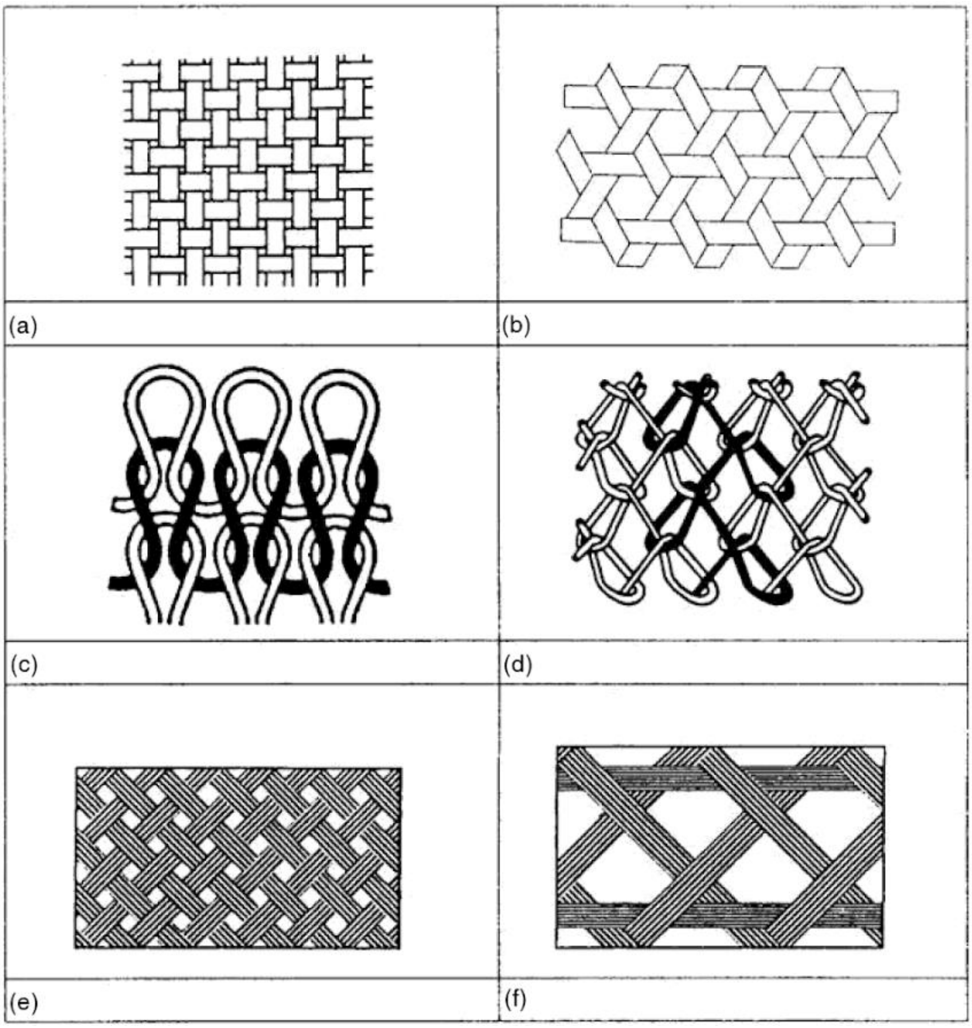


Figure 4 Two-dimensional fibre orientations with continuous fibres (Mallick, 2008)

3.2.1 Determining properties

Composites are made of two or more different materials that together create a unique set of properties. Determining these properties is not straightforward since the materials have different properties together than they have separately. Also, the anisotropy creates challenges for the strength calculations. Manufacturing technique is also affecting the properties of the composite. There are different methods created to evaluate the properties such as modulus of elasticity, density and shear modulus. The most common way is to use the volume proportions. The calculations made with volume proportions can only be used for simple composites that are considered to be layer-isotropic in fibers, isotropic in matrix and free

of porosity. These calculations are estimations but provide good guidelines for composite design. (Saarela et. al. 2003)

This method is called the rule of mixtures and it is derived from Hooke's law (1). Below, the rule of mixture is used to evaluate the Young's modulus in fibre reinforced composite. Strains are assumed to be equal in all components.

$$\sigma = \varepsilon E \tag{1}$$

$$F = \sigma * A \tag{2}$$

$$F_f = A_f E_f \varepsilon \tag{3}$$

$$F_m = A_m E_m \varepsilon \tag{4}$$

$$E = \frac{\sigma}{\varepsilon} = \frac{\frac{F}{A}}{\varepsilon} = \frac{F_f + F_m}{\varepsilon A} = \frac{A_f E_f + A_m E_m}{A} = V_f E_f + V_m E_m = V_f E_f + (1 - V_f) E_m \tag{5}$$

$\sigma = Stress$

$\varepsilon = Strain$

$E = Young's\ modulus$

$F_f = Load\ carried\ by\ fibres$

$F_m = Load\ carried\ by\ matrix\ material$

The fiber content is the most essential factor affecting the properties of the composite. The theoretical maximum of the percentage of fiber volume is ~91% when the cylindrical fibers are tightly packed in the same orientation. However, basically always the fibers are packed more loosely and the structure of composites requires that there is matrix material between each fiber to bond them together and transfer loads. This leads to the practical maximum fiber content of about 65-70% of volume. With most of the manufacturing techniques the fiber content is below the maximum, e.g. prepreg ~60%, RTM ~50%. (Saarela et. al. 2003)

4 Systematic product development

Product development is probably the most essential part of the company when it comes to long term success in the markets. No matter how good your product or core business is, it will need improving and development in order to stay on top of the market. Product development, depending on the field, is a very diverse task that usually requires skills of many different parts of the organization, for example engineering, finances and production. In many companies, the product development process is being carried out by a single design engineer and the design process is based on the line of thoughts of one person. It is part of human nature to, sometimes unintentionally, stick with one of the first possible solutions and fail to see other approaches and aspects.

Design process has a very central role in the company. The products that come out in the market, individually or as a part of machine, have properties that are determined by the designer. These properties include function, safety, maintenance, recycling etc. The aforementioned properties have high importance in the product's lifecycle so it is obvious that the responsibilities the designers carry out are high. If the design process itself is lacking guidelines, is not flexible and repeatable, the chances of design process and design outcomes being not innovative, ineffective and more time consuming are high. (Pahl, Beitz, 1995, p. 7-9)

4.1 Theory

The basic idea behind the systematic product development is splitting the development process into smaller steps and making the whole process iterative. The design methodology should be problem-directed and foster innovativeness to help designer reach possible solutions faster and more directly. When the requirements are clearly stated and separated from inessential attributes and "hopes", the designing is more straightforward and the problems are being solved systematically. (Pahl et. al. 1995)

4.2 Process

The steps of the design process have different names in different sources (e.g. Pahl et. al. 1995; Ulrich, Eppinger 1995) but the basic principles of the phases are the same.

1. Planning and Clarifying the task

Before thinking about any solution, the task or the problem should be analyzed. Market research is important especially when developing new products. The product usually has requirements that are essential but also a set of attributes that are considered to be inessential and not obligatory. The whole development will be based on the list of requirements, so it is a vital part of the process. All requirements should be measurable. Abstraction is a useful method to find out the problems.

↓

List of Requirements

↓

2. Conceptual design

After the list of requirements is gathered, the product developers start the conceptual design. This phase includes identifying the essential problems and the main functions. Sometimes it is also beneficial to break the main functions down into sub-functions to find the best solutions for specific needs. At this phase, even the wildest possible concepts should be brought up, as they might offer solutions indirectly to some other problems. Brainstorming is a useful tool to produce different ideas.

↓

Concepts

↓

3. Embodiment design

In this phase, the concepts built in the previous phase will be developed further and into more details. The list of requirements is guiding also the embodiment design through the requirements in shape etc. Depending on the product, about 3 concepts should be evaluated according to technical and economical criteria. If list the of requirements has weighting values, they can be used to assist evaluation.

Preliminary layout

4. Detail design

The preliminary layout chosen in the previous phase is now developed in to the final stage. All the details should be now chosen and documented and manufacturing drawings made. Also things like transportation and assembly instructions should be prepared. The list of requirements should be once more checked to ensure that the product fulfils all the stated requirements.

Product documentation

5. Testing and prototyping

The developed product is simulated and, if possible, prototyped. The test shows whether the product works as planned and if there has been mistakes in the earlier stages of the product development. Modern rapid prototyping techniques, such as 3D-printing, make the prototyping much easier and cheaper. Testing can partly be made during earlier stages with the help of computer simulations.

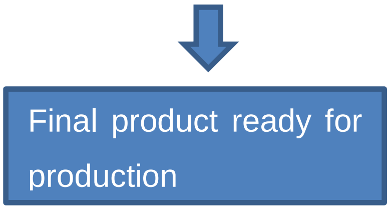


Figure 5 Systematic product development process. Based on Pahl et. al. (1995) and Ulrich et. al. (1995) redrawn by E. Palomäki

4.3 Benefits

The products become more and more multi-technological every day and this creates the need of new processes and methods in product development. The design activities require traditional scientific and engineering knowledge but also experience in the specific field of the product. The systematic approach to development process enhances the collaboration between the professionals in the organization and makes the whole design process more transparent and logical. Like mentioned before, the goal is not to kill the intuition of the designer but rather rationalise the design process and steer the designers from unconscious to conscious and more purposeful solutions. The stepwise process also makes it easier to recognize and reuse the solutions made in previous projects. (Pahl et. al. 1995)

When the list of requirements, market research and project plan are made carefully and in collaboration with designers, salesmen, process specialists, management, production, purchasing and other possible stakeholders, the goal of the product development should be clear to everyone. With the clear goal, designers are more capable of reaching problem-free concepts that fulfil the requirements and the time spent on unnecessary or ineffective designs is minimized. The product should also be inspected and revised often to avoid human errors and to ensure that the requirements and regulations are fulfilled. (Ahola, Hovila, Karhunen, K. Nevala, Schäfer, T. Nevala, 2011)

4.4 Requirements of the new axis system

The systematic approach to product development is usually most beneficial for new parts and complete systems that include many parts. However, the process is flexible and it can also be used to already existing parts that require revisioning. The list of requirements is one of the most useful tools also in single part development. If the list of requirements is properly built with exact and measurable values, the designer can refer to the list whenever guidelines and goals are needed. For example, the requirement for mass is a simple and straightforward "tool" for the designer. When the designer reaches preliminary concepts during the modelling, he/she can always check the mass properties and see if the concept requires mass reduction. This way the time spent in unnecessary design is minimized and the prototypes meet the requirements more often already at the first attempt.

List of requirements *High-speed OF X-axis*		
D/W	**Requirements**	**Comments**
	Geometry	
Demand	Length min. 800 mm	
Wish	Identical geometry; usable on both sides	
	Kinematics	
Demand	Acceleration 2 G	
Wish	Acceleration 2,5 G	
	Forces	
Demand	Mass of the whole system less than 40,77 kg	Determined by motor power
Wish	Mass of the whole system less than 32,62 kg	
	Energy	
Demand	Maximum power 1,5 kW	
	Assembly	
Wish	Assembling can be done with existing methods	
	Recycling	
Wish	Axis material should be recyclable	
	Cost	
Wish	Price should be lower than existing models	

Figure 6 List of requirements of the high-speed OF X-axis

5 Design and analysis of the new axis

The conceptual design process started with the creation of sketch assembly where the future concepts can easily be fitted to roughly see their suitability. Cencorp 1000 OF EVO was used as a template and all the unnecessary parts, such as the case and the old XZW-axis were removed. The Y-direction ball screws were replaced with a linear motor to make the assembly as similar to the new machine as possible. Since the new high-speed machine does not exist yet, fitting the axis to the 1000 OF EVO is just a way to make sure the scale of the concepts is roughly correct. The new machine might have different frame, which will then affect the dimensions of the axis, but the possible changes will be minor.

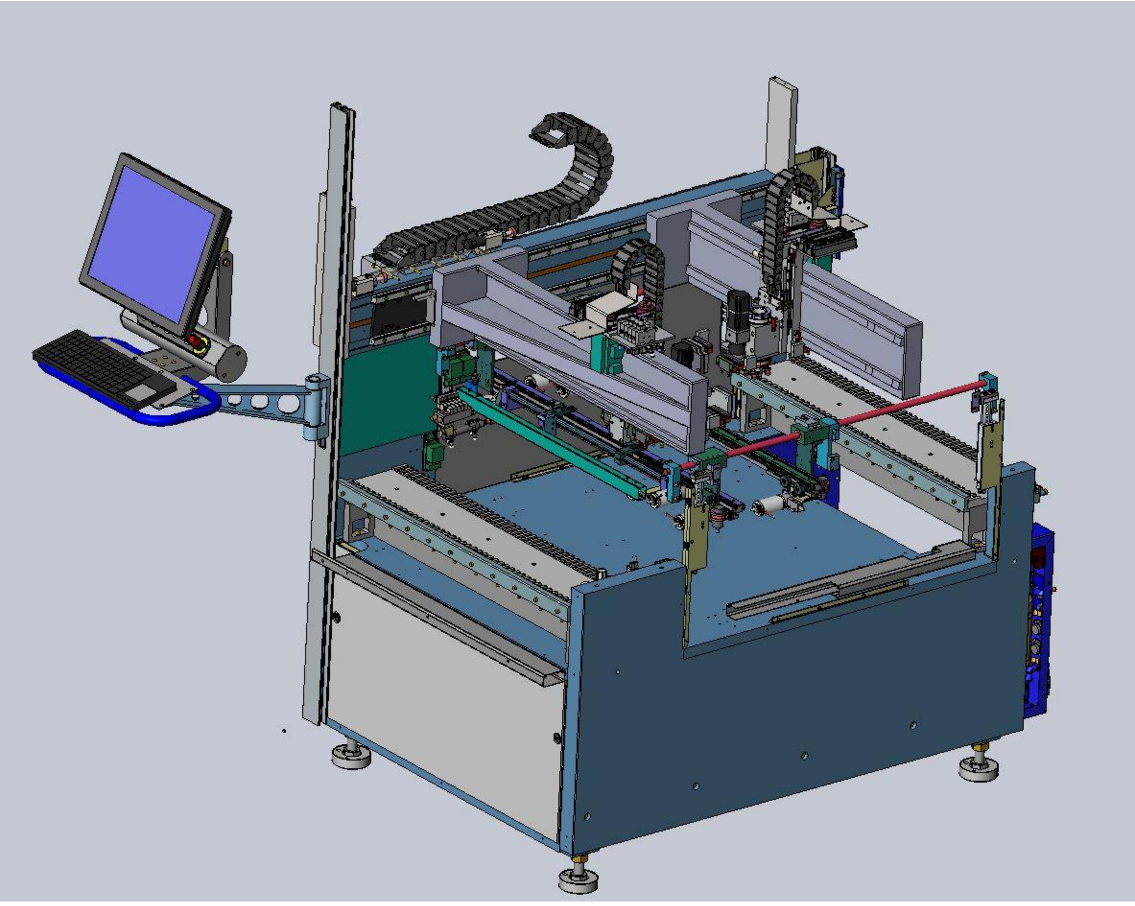


Figure 7 Sketch of the high-speed OF

5.1 Calculation of the allowed mass

To reach the required acceleration of the axis, a calculation for the allowed mass is necessary. Since the motor power is set to be at 1,5kW, it will be the factor determining the allowed mass. The linear motor used is Omron R88L-EC-FW-0612-APLC. This motor has a momentary maximum force of 800N and continuous force of 320N (Omron, 2007). The allowed mass of the axis system, including the axis itself, gripper and everything else that is moved by the linear motor, can be calculated directly with Newtons II law (6).

$$F = ma \rightarrow m = \frac{F}{a} \tag{6}$$

$$a_{target} = 2{,}5G = 9{,}81 \frac{m}{s^2} * 2{,}5 = 24{,}525\ \frac{m}{s^2} \tag{7}$$

$$a_{minimum} = 2G = 9{,}81 \frac{m}{s^2} * 2 = 19{,}62\ \frac{m}{s^2} \tag{8}$$

$$m_{target} = \frac{800N}{24{,}525\ \frac{m}{s^2}} = 32{,}62\ kg \tag{9}$$

$$m_{maximum} = \frac{800N}{19{,}62\ \frac{m}{s^2}} = 40{,}77\ kg \tag{10}$$

The distances that the X-axis travels are quite short. For this reason, the force coming from the Y-direction linear motor is almost pulsating. In practice, the axis will never travel at its maximum speed, but it will either accelerate or decelerate. For this reason, it is safe to set the allowed mass to the one calculated with motor's momentary force. The mass does not include only the axis itself but also linear guides, the ZW-unit, energy chains, sensors, bolts and everything else that will be attached to the X-axis.

5.2 3D-models

The 3D modelling was made according to hand-drawn sketches. Three different models were made and then analysed. All models have advantages and disadvantages but the most important evaluation value was the weight and the stiffness. The biggest challenges are the strict mass requirement and the symmetricity of the structure. It is of course possible to manufacture two different parts that are mirror images from each other, but this would increase the costs since two molds would have to be made and the production volumes would be lower.

The 3D-models are made with SolidWorks and the models are simple, meaning no threads, holes and real fillets are modelled. The simplicity of the models help to analyse the structures with FEM. A design that is more detailed is also unnecessary at this stage of the design process.

The two rectangles drawn on each model represent the linear guides. A rough design of the linear guides allows the application of the forces more precisely and more realistically. They also help the designer to perceive the actual size of the part.

This phase is the third step in the systematic product development procedure. Based on the hand-drawn sketches and ideas, the following concepts are the ones that will be studied further.

5.2.1 The first concept

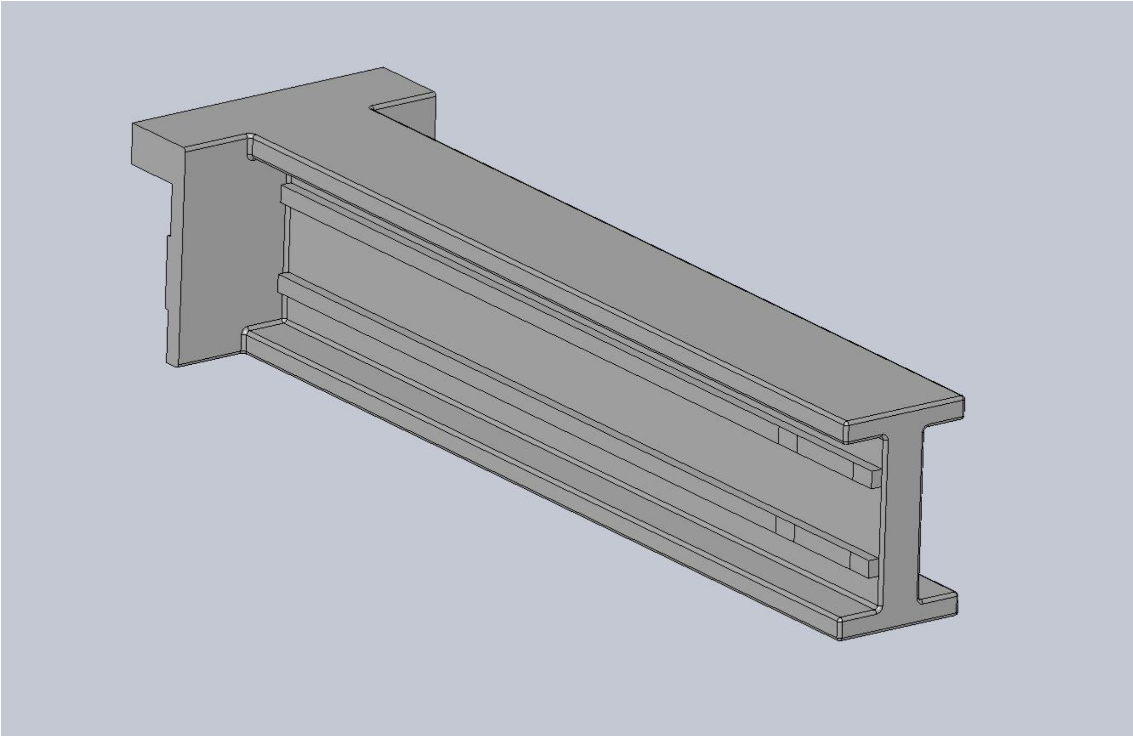


Figure 8 The first concept

In the “I-beam” concept, the basic idea is the symmetric structure on both sides. This model could be used in either side of the machine. The design is also simple and the manufacturing would not require anything special. The flat surface on top of the axis would also be a useful platform to attach for example the energy chains and other necessary components.

The mass of the concept is **15,3 kilograms**.

5.2.2 The second concept

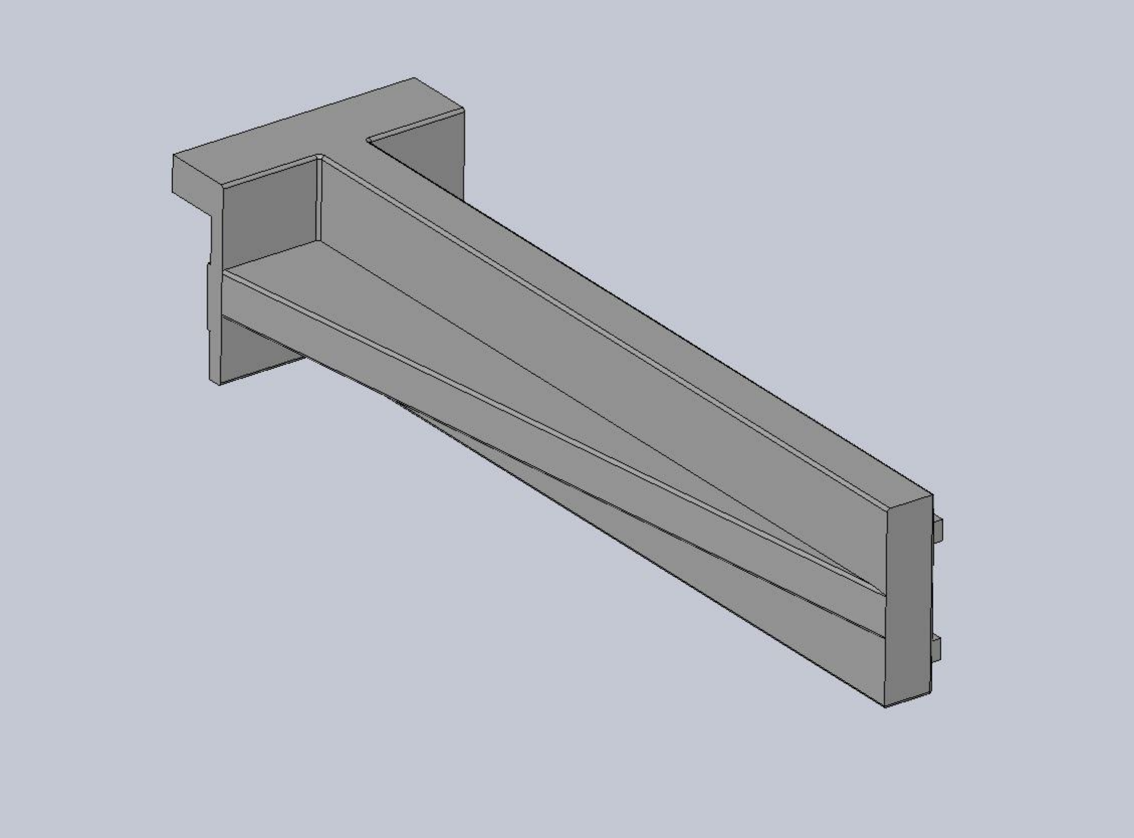


Figure 9 The second concept

The idea in this concept is as stiff structure as possible. The structure is also simple and manufacturing would be simple. This axis would require manufacturing two different axis because the structure is not usable on both sides. The simplicity of the surface on the linear guide side would make the design of the new ZW-axis easy because the flat surface does not restrict it anyway.

The mass of the second concept is **16,4 kilograms**.

5.2.3 The third concept

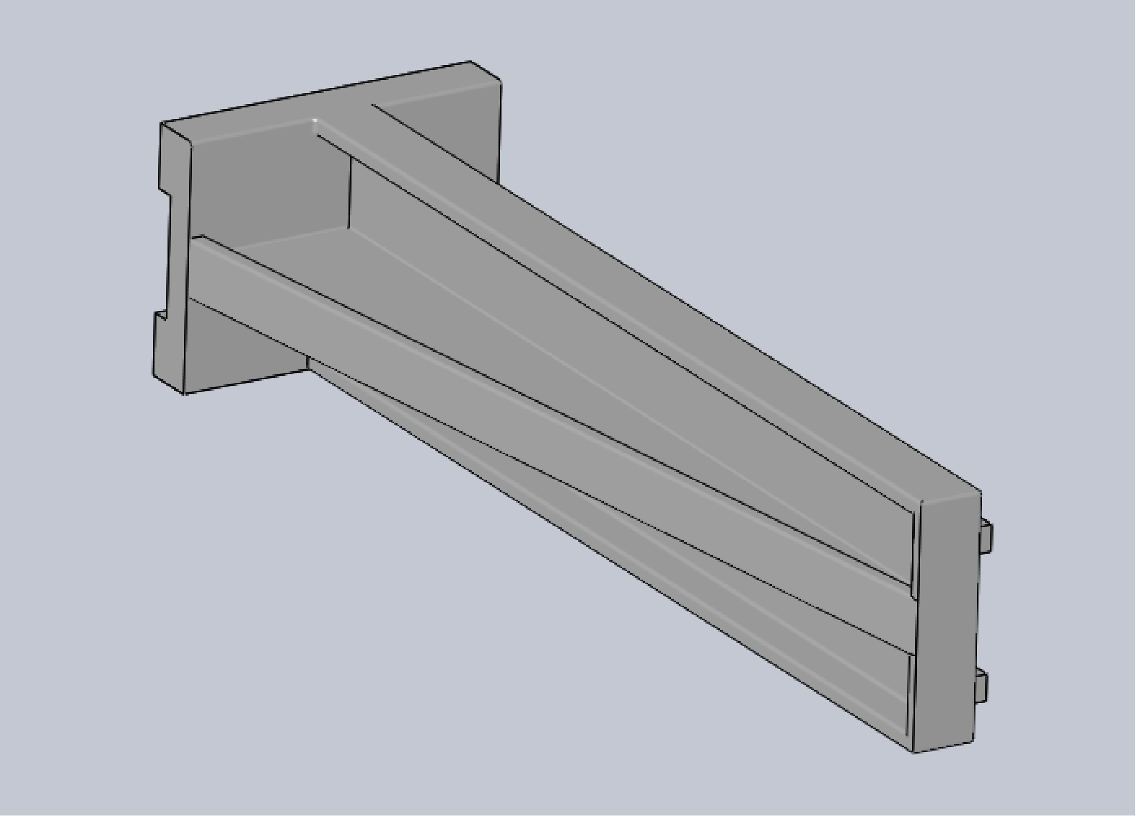


Figure 10 The third concept

This concept is developed from the second concept. The structure is lightened to reach as low weight as possible while trying to preserve the stiffness in the critical directions. The optimization was made by removing material from the areas that are not transferring or carrying loads. The manufacturing aspects were also considered, e.g. sufficient wall thickness for metal thread elements that are needed to attach the linear guides. The optimization leads to a cross-section of an asymmetric profile.

The motor side of the axis is also changed to enable the usage of the same axis in either side of the machine. This change requires the linear motor to be moved to the inner side of the machine. With symmetric fixing points the axis can be flipped on either side (see Figure 7).

The mass of the concept is **9,9 kilograms**.

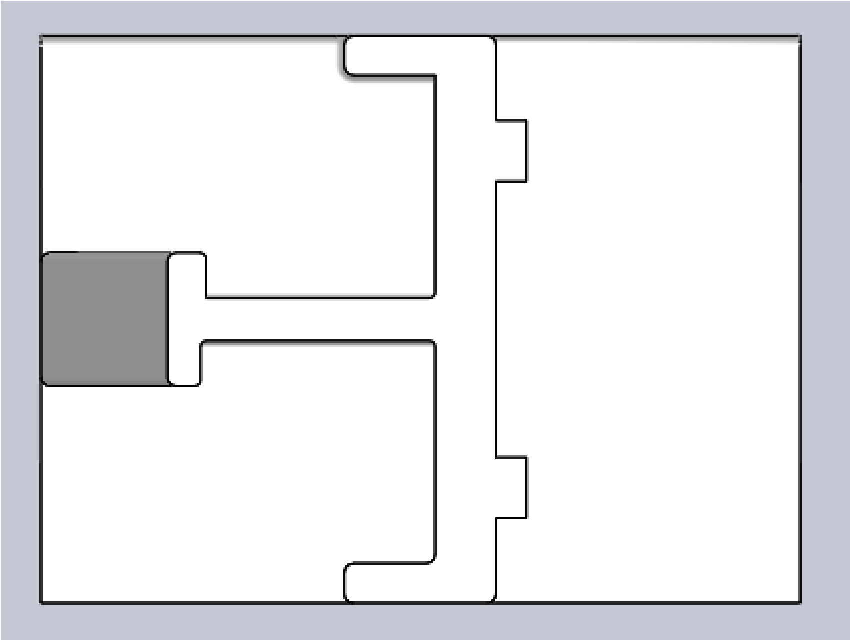


Figure 11 Cross-section of concept three

5.3 Material properties

Like mentioned in chapter 3, determining properties of a composite is not as straightforward as with metallic materials. Properties are greatly affected by the manufacturing technique and producing identical fibre orientations and fibre/matrix ratios is impossible. A method to evaluate Young's modulus is presented in equation 1. The calculations are estimations and more often the composite manufacturing companies rely on practical test data when doing the calculations.

The following properties include a sufficient factor of safety meaning that the value of Young's Modulus is higher in reality, but a lower value is used in the calculations to compensate possible human or manufacturing errors.

Carbon fiber/epoxy composite	
Isotropic Young's Modulus (E)	45 GPa
Density	1550 kg/m^3
Typical fibre percentage by volume	55%

Figure 12 Carbon fiber/epoxy composite properties (CSI-Composites Oy, 2018)

5.4 Calculation of the inertial forces

To conduct the structural analysis of the concepts, it is required to calculate the inertial forces caused by the acceleration, deceleration and the masses. Due to the early stage of the project, there are no exact values of the ZW-axis and gripper masses available yet. For the analysis, the mass of the existing ZW-axis is used. The mass of this axis will most likely be reduced also, which means that the following analysis is on the safe side. The lowered mass will cause lower inertial forces thus lower displacements and stresses.

5.4.1 Moment caused by gripper

The gripper is attached to the ZW-axis and its function is to pick and place the components. The grippers mass is causing different torque to the X-axis depending on the position of the gripper in Z-direction and the acceleration in Y-direction. To get the maximum displacements, the calculation is made with the lowest point of Z-axis and with biggest acceleration in Y-direction. The inertial forces of the gripper are transferred to the X-axis through the linear guides and action is equivalent to a force couple; forces in the upper guide and lower guide are opposite to each other.

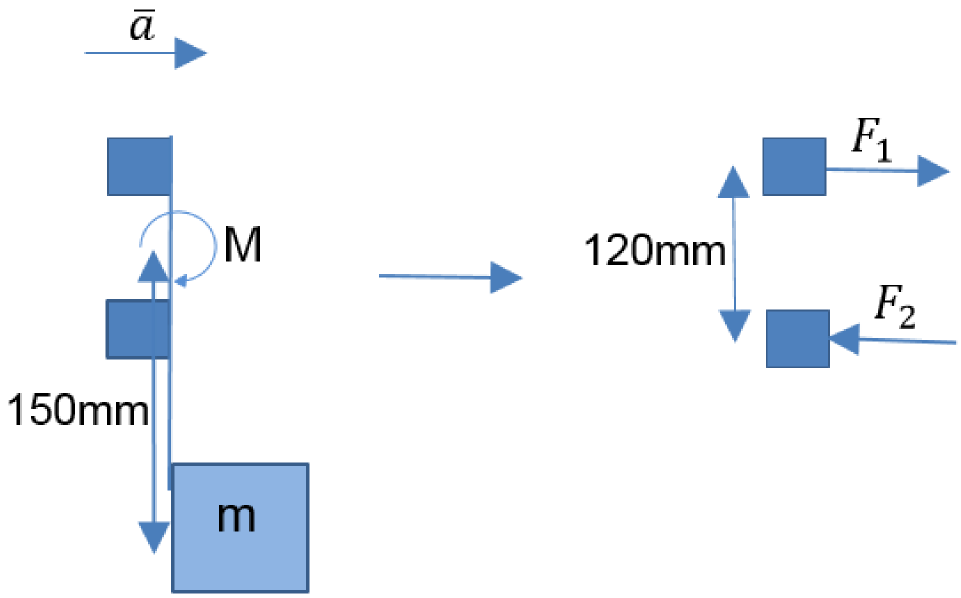
$$F = ma = 15kg * 24{,}525\frac{m}{s^2} = 367{,}9\ N \tag{11}$$

$$M = Fz = 367{,}9N * 0{,}15m = 55{,}185\ Nm \tag{12}$$

$z = 0{,}15m$

$m = 15kg$

$a = 24{,}525\frac{m}{s^2}$



$$F_1 = F_2$$

$$M = F_1 * 0{,}06m = \frac{55{,}185\ Nm}{2} \rightarrow F_1 = \frac{55{,}185\ Nm}{2 * 0{,}06m} = 459{,}875N \qquad (13)$$

In the static analysis, the moment caused by the gripper's mass can be simulated with a force couple acting on the linear guides. The moment is calculated in the situation where the gripper is at its lowest position and the acceleration is highest. The higher the gripper is when the acceleration happens, the lower the torsion in the X-axis is.

5.5 FE-analysis

The FE-analysis was conducted using SolidWorks Simulation. Even though the highest loads that the axis faces are the inertial forces appearing in dynamic situations, the static analysis can be used to simulate the moment when the loads are at their highest, i.e. the acceleration is the highest. In this case, the most essential values retrieved from the FE-analysis are the displacements and the stresses occurring in the axis. The loads applied on each model are:

1. Gravitational force of 9,81 m/s^2 downwards and 24,525 m/s^2 (2,5G) to the side of the movement. Described with thick red arrows.

2. Forces of 460N representing the moment caused by gripper's inertial forces in the acceleration, affecting on the linear guides. Described with purple arrows.
3. 150N force downwards caused by static mass of ZW-axis and gripper, affecting on the linear guides. Described with purple arrows.

The deformed shapes are showed with 100x magnification because the displacements are so small.

In addition to the static analysis, a frequency analysis of the concept three will be made to find the lowest natural frequencies of the axis and ensure that the excitation from the machine usage is not close to these.

5.5.1 The first concept

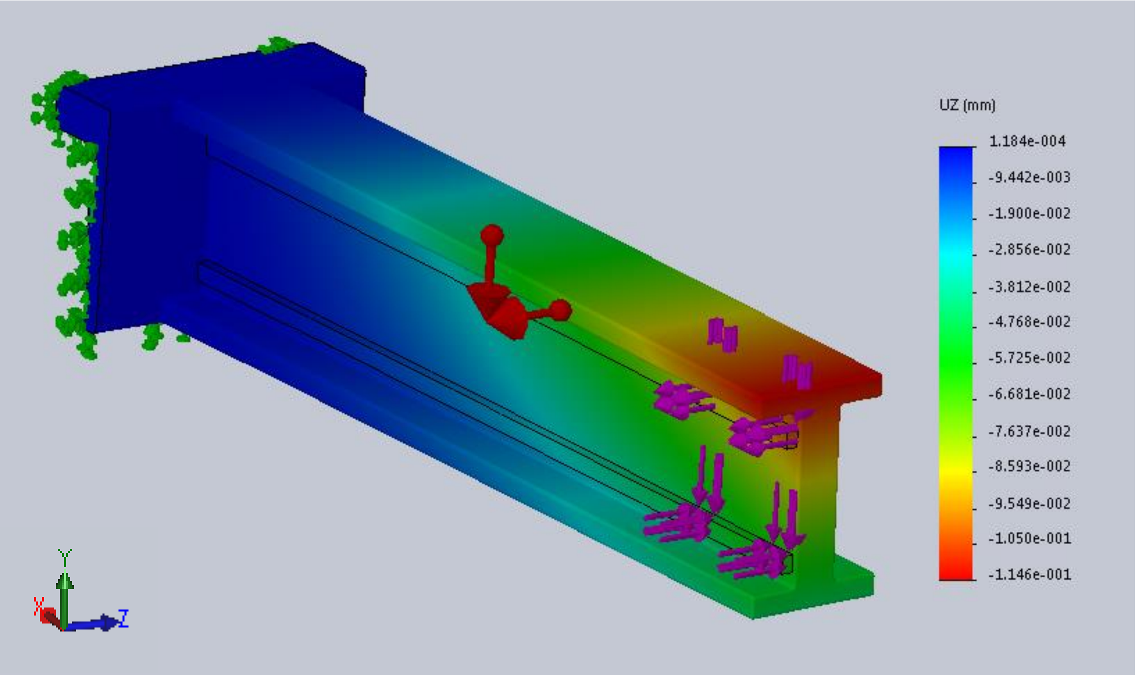


Figure 13 Displacement of the first concept in Z-direction, FEM-programs coordinate system

The maximum displacement in FEM-programs Z-direction (Y-direction in Cencorp machines) is **0,1146 mm**. The maximum displacement occurs in the upper web of the I-profile because the torsion is causing twist to the axis.

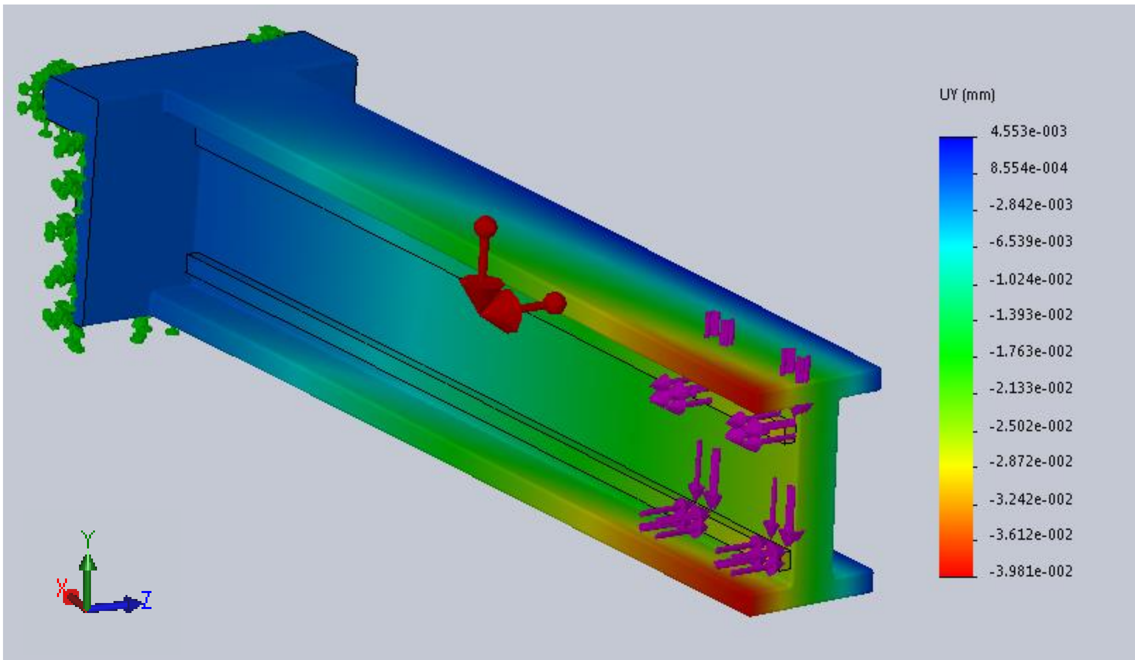


Figure 14 Displacement of the first concept in Y-direction, FEM-programs coordinate system

The maximum displacement in FEM-programs Y-direction (Z-direction in Cencorp machines) is **0,03981 mm**. Also this displacement is caused by the torsion so it occurs mostly on the gripper’s side of the axis.

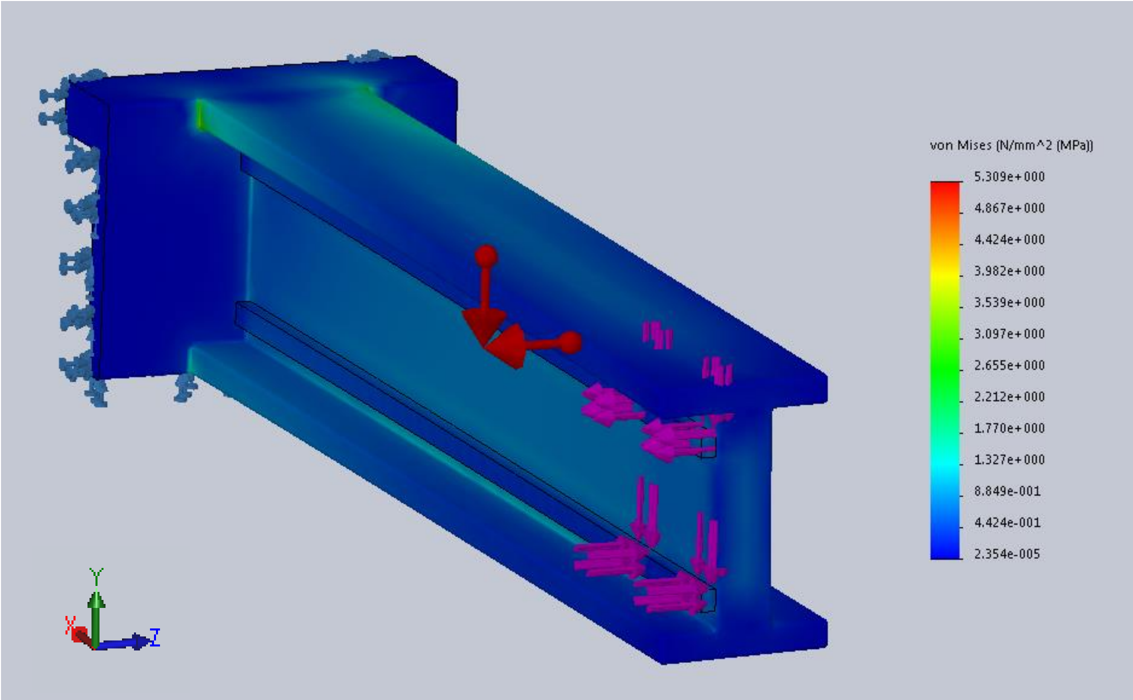


Figure 15 Von Mises stress in the first concept

Von Mises stress is based on Von Mises yield criterion. In addition to the normal stresses this methods takes shear stresses into account. The shear stresses cause shearing strains and these cause principal stresses inside the structure. (Jones, 2008)

$$\sigma_{eq} = \sqrt{\sigma^2 + 3\tau^2} \tag{14}$$

5.5.2 The second concept

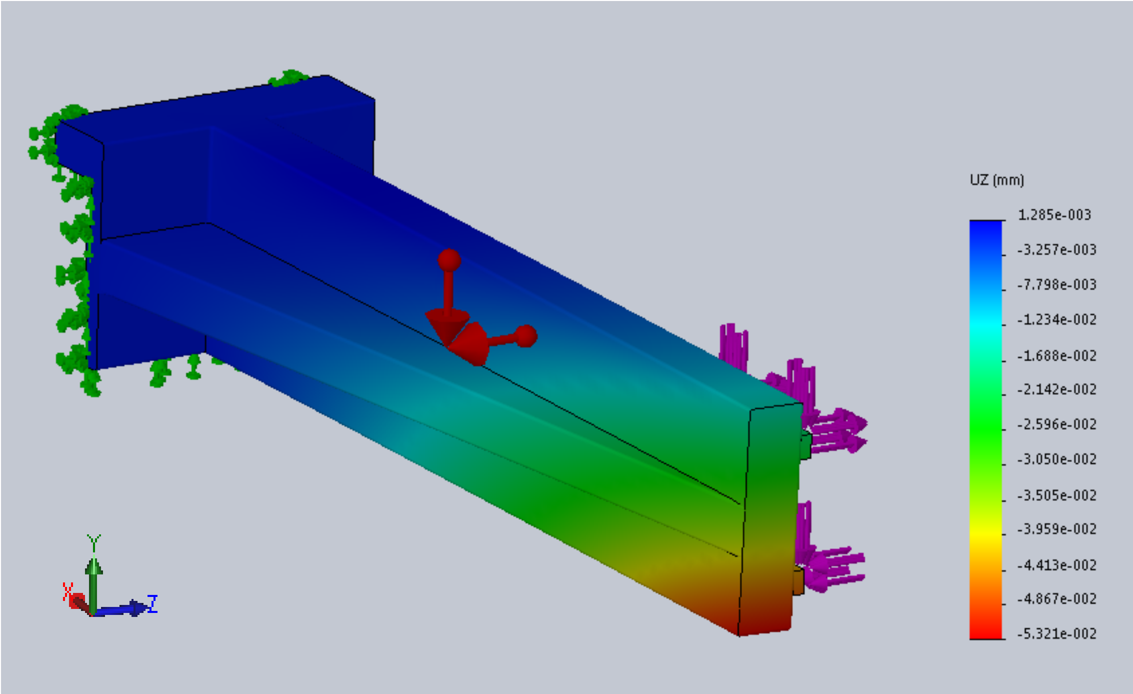


Figure 16 Displacement of the second concept in Z-direction, local coordinate system

The maximum displacement of the second concept in local Z-direction (Y-direction in Cencorp machines) is **0,05321 mm.** If this concept is developed further, the wall thicknesses should be revised. The displacements are extremely small and local which means that excess and unnecessary material should be removed. Concept 3 is optimized from concept 2, but to ease the manufacturing the concept 2 could also be studied further.

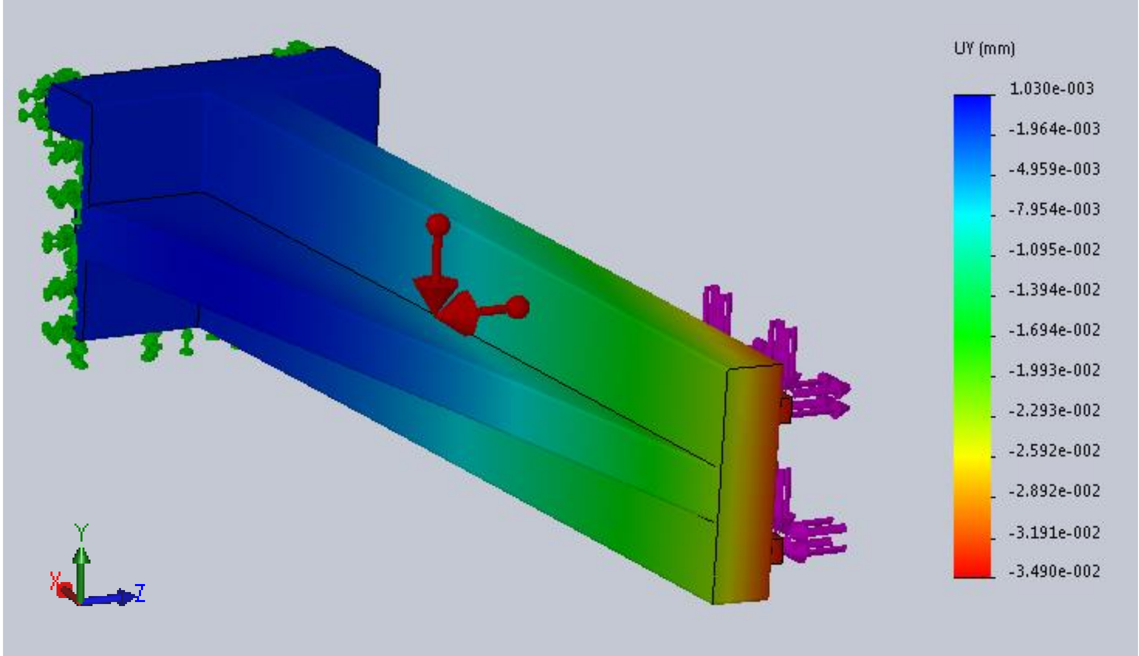


Figure 17 Displacement of the second concept in Y-direction, local coordinate system

The maximum displacement of the second concept in local Y-direction (Z-direction in Cencorp machines) is **0,0349 mm.**

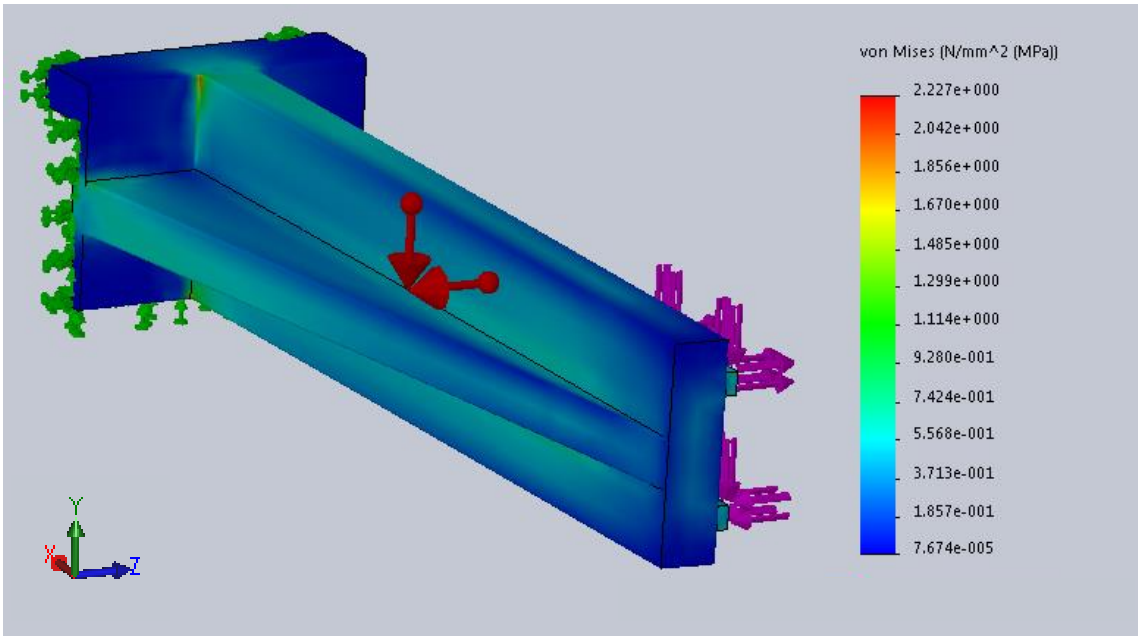


Figure 18 Von Mises stress in the second concept

The maximum equivalent stress in the second concept is 2,227 N/mm^2. This stress is also very locally in the fillets, which means that the stresses will not cause any problems for the axis functions.

5.5.3 The third concept

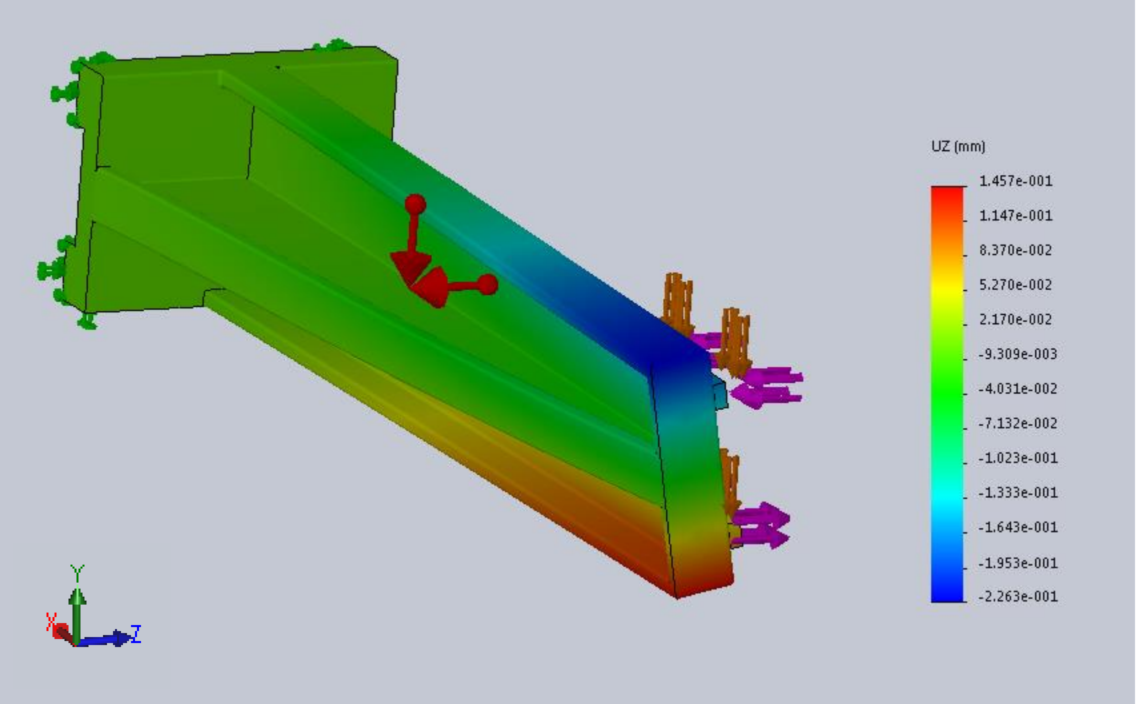


Figure 19 Displacement of the third concept in Z-direction, local coordinate system

The maximum displacement of the third concept in local Z-direction (Y-direction in Cencorp machines) is **0,2263 mm.** The axis is twisting because of grippers inertial forces. In the real situation, the steel linear guides will however stiffen the axis and the machine can be programmed so that the gripper is not in the lowest position during the highest accelerations. The torsional stiffness can also be increased by increasing the width of the horizontal walls, i.e. the horizontal parts of the C-profile.

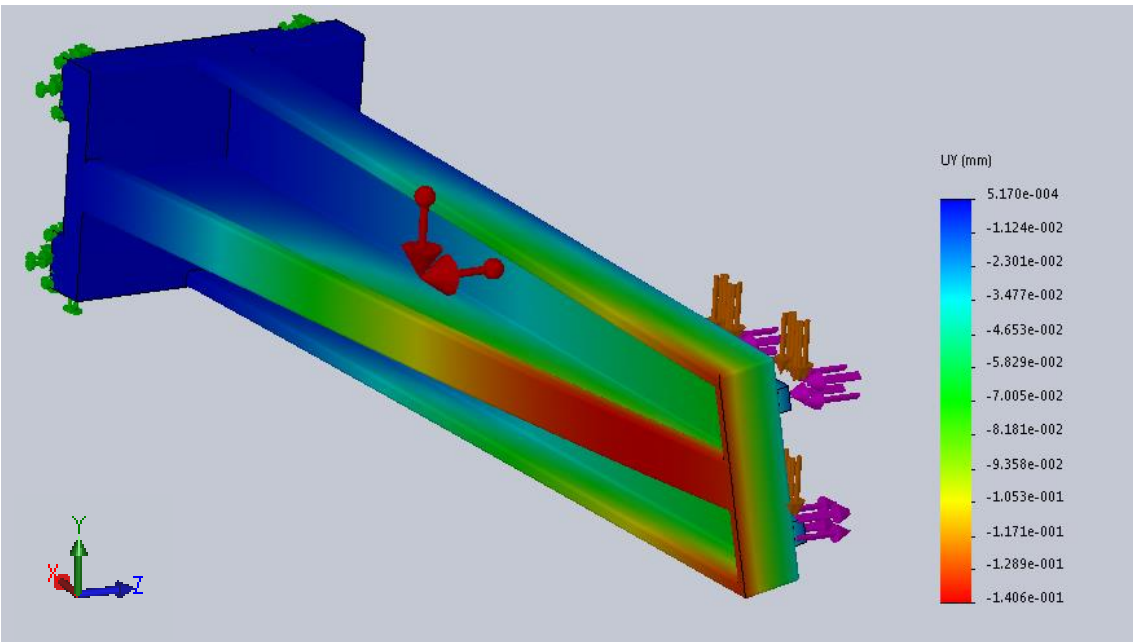


Figure 20 Displacement of the third concept in Y-direction, local coordinate system

The maximum displacement of the third concept in local Y-direction (Z-direction in Cencorp machines) is **0,1406 mm**. As figure 20 shows, the displacement is not directly downwards. The twist of the axis is causing the biggest displacements also in local Y-direction. Without the twist, the maximum displacement is in the green zones of figure 20 with a value of around 0,08 mm. The twist can be prevented by lifting the gripper to the upmost position before the maximum acceleration.

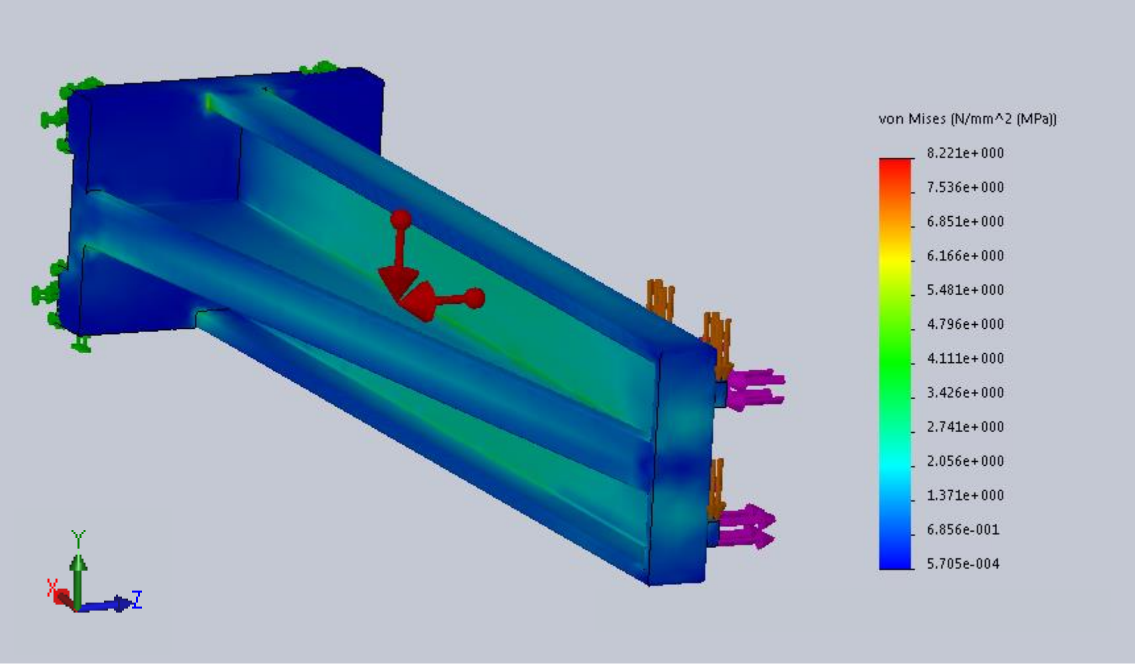


Figure 21 Von Mises stress in the third concept

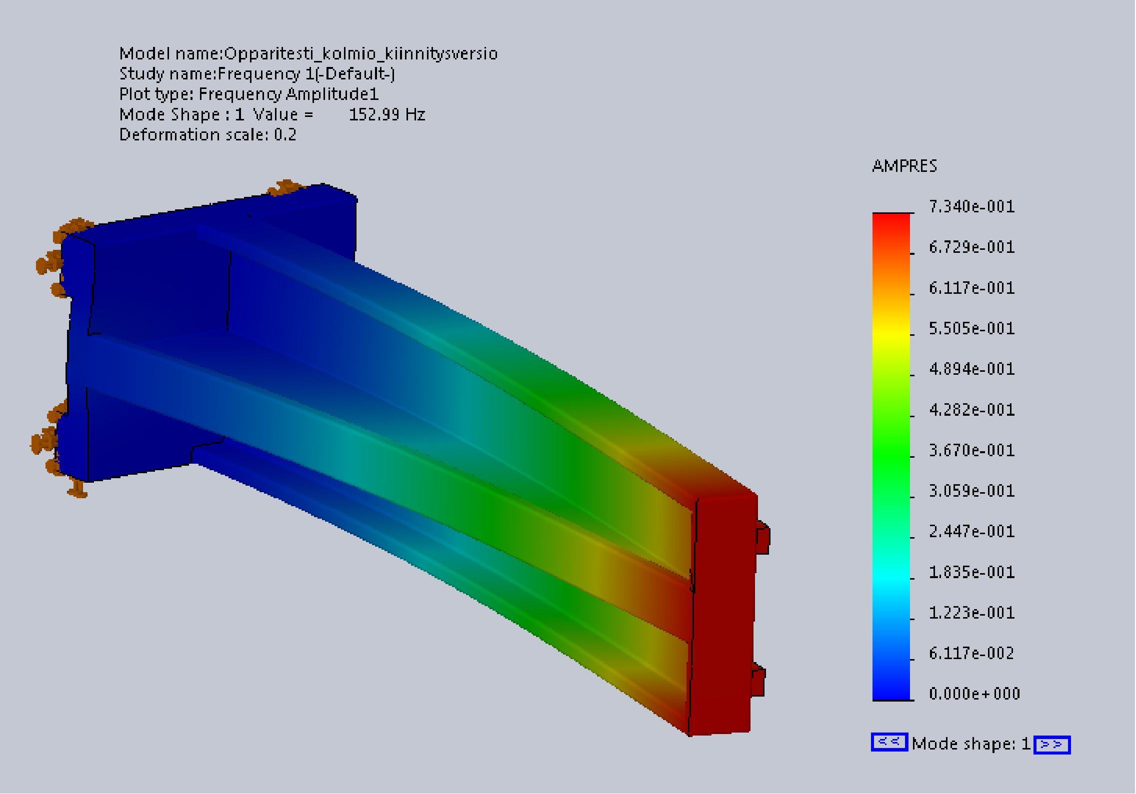


Figure 22 Lowest natural frequency and shape of the third concept

The frequency study shows the lowest natural frequency of the third concept. Natural frequency is the frequency in which the structure vibrates when it is free of damping and external forces. A system usually has many natural frequencies and shapes of vibration. (Hatakka, Saari, Sirviö, Viiri, Yrjänäinen, 2005)

Natural frequency is an important attribute of machine parts, because if the system has an internal or external excitation that is close to the natural frequency of a machine part, there is a risk of “reckless” vibration that can lead to a breakage of the system. The lowest natural frequency is at 152,99 Hz which means that the Y-movement should be run approximately 153 times per second which is not possible. The possible external excitation is damped through other machine parts and is very unlikely to cause problems in the machine.

5.6 Mass comparison

Since the mass reduction is the main goal of the material change and new design, it is necessary to compare different materials and their impact on the mass. The most likely competitor to the carbon fiber reinforced plastic is aluminium, either cast or machined. Also, the existing axis of Cencorp 850 OF is added to the comparison to help elucidate the masses in practice.

	Concept 1	Concept 2	Concept 3	850 OF
Carbon fibre/epoxy resin (55/45 V%)	15327.01 g	16401.35 g	9890.04 g	16214.23 g
EN AW-6082	26698.66 g	29427.62 g	17227.82 g	
EN AW-7075	27786.38 g	30626.52	17929.69 g	

Figure 23 Comparison between different materials

5.7 Results

The FE-analysis presents the displacements of different concepts. At this point of the project, it seems that each of the concepts would be rigid enough to withstand 2,5G acceleration. The most flexible direction of concepts 2 and 3 is the twist around the length axis, which is caused by the mass of the gripper when it is at its lowest position. By lifting the gripper up before accelerating, the moment will be reduced significantly and the displacements are also smaller.

It is also worth noticing that the FE-analysis is made for the axis alone. In the ready product, the steel linear guides will stiffen the structure lowering the displacements in all directions. Also other components such as bolts, energy chains and X-movement actuator will be attached to the axis. This will increase the mass and the addition should be roughly calculated before prototyping to ensure that the maximum allowed mass is not exceeded.

The Von Mises stresses in each concept are very small and the material yielding is not a risk with these loads. When the manufacturing technique is decided in the future, a closer analysis of the stresses might be needed. If the axis will be built from many parts and then glued together, the shear stresses should be checked to assure the safety of glued joints.

6 Conclusion

During the first discussions about the thesis, the goal was to figure out whether it is possible to build a new axis from a composite material so that it is rigid and strong enough to withstand accelerations up to 2,5G. During the early phase of the study, the goal was moved towards conceptual, preliminary designing of the new axis. The early stage of the project created some challenges but also possibilities, since a completely new machine gave the possibility to design something totally new. The conceptual design faced similar problems as described in chapter 4. After the first eligible idea it was hard to see other possible solutions. Going through the list of requirements and consulting other designers eventually helped to create different concepts.

The results of the FE-analysis are very promising. The deformations in all directions are smaller than expected and the required stiffness seems to be reachable with a structure that is almost 50% lighter than the existing axis. However, the structure still requires a lot of inspection about practical matters. The manufacturability needs to be studied with a company that has practical experience about the manufacturing of carbon fiber composites. Also, the suitability of the structure should be checked with the requirements set to the process itself. Reachability to the component feeders and to the maximum size PCB should be checked when the design of the machine's frame is finished.

Only the first steps of the systematic product development process were used in this development project. However, the process is worth keeping in mind in the future projects. Especially the collaboration between persons from different departments should be increased to reach better solutions in the mechanical designs.

6.1 Suggestions for the future of the project

The high-speed OF –project is very intriguing and will definitely have demand in the market. To reach a final product that really has innovative and competitive features, the development should be done systematically. The problems in already existing machines should be processed and documented in tight collabo-

ration with all internal stakeholders: process specialists, ramp-up engineers, international service engineers, salesmen, assemblers and mechanical- and electrical designers. If the knowledge of the existing problems is not transferred to the product development department, the change towards better and more functional products will never happen.

The new machine offers a great chance to develop solutions for already existing issues and create new innovative solutions. The new axis is a good start and the eagerness towards daringly new and innovative machine parts should be preserved and not allowed to be distracted by the constant hurry and lack of resources.

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