Design and experimental evaluation of micro embossing system

Emad A. Poshtan

Department of Mechanical Engineering
Blekinge Institute of Technology
Karlskrona, Sweden
2009

Supervisors: Ansel Berghuvud, Ph.D Mech Eng, BTH
Professor Dr.-Ing. Christian Brecher, RWTH Aachen
Dipl.-Ing. Christoph Baum, Fraunhofer Institute, IPT, Aachen
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Abstract:
Within the project, a mechanical device for the realization of the needed embossing operations will be developed. Focus of the work is the mechanical design of the embossing unit, which requires careful investigation in order to find suitable solutions for the mechanical setup of this ultra-precise device. Subsequent to the design process, the start-up of the embossing unit will be supervised.

Keywords:
Embossing system, precision design, linear system, rotary system, embossing head tool, conceptual design, detailed design, Solidworks.
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In this report some of the figures are omitted due to secrecy agreement with Fraunhofer Institute. For further information regarding this project you may contact Fraunhofer Institute IPT, Aachen, Germany.

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Emad A. Poshtan
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1 Notation

$A$ Area

$a_{\text{max}}$ Maximum acceleration

$B$ Thickness

$C_0$ Static load rating

$C_f$ Unit conversation factor

$D$ Outer diameter

$d$ Inner diameter

$E$ Young’s modulus

$F$ Force

$F_l$ Force due the loads

$F_p$ Peak force

$F_{\text{RMS}}$ RMS force

$F_m$ Acceleration of mass

$f$ Frequency

$G$ Shear modulus

$g$ Acceleration of gravity

$J$ Mass moment of Inertia

$j_{\text{max}}$ Maximum Jerk
\( k \)  Spring coefficient

\( M \)  Torque

\( m \)  Mass

\( m_{LC} \)  Load and actuator coil mass

\( p \)  Smoothness parameter

\( r \)  Radius

\( S_f \)  Safety factor

\( T \)  Torque

\( T_f \)  Friction torque

\( t \)  Time

\( V_{TRI} \)  Average speed of triangular movement

\( \alpha \)  Load acceleration

\( \beta \)  Angle

\( \varepsilon \)  Prediction error

\( \tau_c \)  Calculated shear stress

\( \tau_F \)  Final shear stress
### Abbreviations

<table>
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<th>Abbreviation</th>
<th>Description</th>
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<tr>
<td>CFK</td>
<td>Carbon Faser verstärkter Kunststoff (Carbon Fiber Composite)</td>
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<tr>
<td>DDR</td>
<td>Direct Drive Rotary (drive)</td>
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2 Introduction

Light plays a fundamental and integral role in our modern life. Product development toward sustainability and CO2 emissions in one hand and quality improvement and production cost in another hand are the issues that industry faces in this field. This creates a demand for increasingly complex, durable, energy efficient and low cost lighting solutions. One solution is the development of energy efficient lighting systems with functional optical surfaces. A comprehensive research approach, which integrates both mold making and mass replication, utilized adaptive hot embossing technology to microstructure large surface components. This technology encompasses a wider range of materials and geometric forms, and can be used to produce a new generation of innovative, high added value products.

![Figure 2.1. Background lighting for screen applications.](image)

The flexible patterning of micro Structures using embossing technology will address the limitations of state-of-art micro machining technologies and optical design calculation methods related to the production function of functional optical elements on large surfaces. The project is applicable in
different light management areas like: backlight modulated LCD, street lighting and indoor lighting.

Within this work a mechanical device for the realization of the needed embossing operations will be designed and developed. Focus of the work is the mechanical design of the embossing unit, which requires careful investigation in order to find suitable solutions for the mechanical setup of the ultra-precise device. Subsequent to the design process, the start-up of the embossing unit and experimental evaluation will be supervised.
Light is one of the most fundamental parts of modern living. It is required in almost every aspect of life ranging from simple applications like traffic lights to complex information transmission for example in monitors, displays and TV-sets. In recent years, the new light applications with complex structures become more sophisticated. For example the Monitors are produced with higher quality, larger display area and more complex applications.

Figure 3.1. State-of-the-art lightening solutions.

Light management using optical structured surfaces can be preceded in many aspects such as the optimization of the luminous efficacy of a given lighting solution as well as performance and display characteristics. It is especially applicable in illumination tasks, which use a point light source such as a Light Emitting Diode (LED).

Although using the optically functionalized elements is beneficial, currently only a fraction of the potential of is being utilized. This is due to the production difficulties of these micro structured surfaces such as the required micro meter sized structures, the required flexibility of structure geometries and the required complexity of the structural patterns.

The state-of-the-art micro machining technologies such as cutting processes [3] photolithography and electroplating [4], LIGA lithography process [5] and diamond machining cannot fulfill these requirements in terms of manufacturing capabilities and complex optics design calculation algorithms and cost. The most critical issue with lithography is the limitation to binary structures of 3-dimensional shapes such as vertical grating units. Also, the process has inveterate problems of contamination and waste. Furthermore, for the display panel size more than 70 inches the investment increases exponentially.
Diamond machining of larger surface areas is also extremely time consuming and sensitive to the influences of machining tolerance errors. Figure 3.2 shows diffractive optics structures with different typical geometries. It illustrates the limitations of conventional micro machining technologies with comparing the complex structure to binary or blazed structures.

![Diffractive optics structures](image)

**Figure 3.2. Diffractive optics structures.**

As it discussed before, in diamond machining, the major problem is machining times especially in the production of large-area elements. For example in manufacturing of reflective patterns such as corner cubes however, diamond machining suits well it is very time consuming.

Furthermore, conventional micro machining has many limitations in terms of size and performance of the optically functionalized elements. Although variety of micro structures and geometrical forms can be manufactured today, there are significant limits in terms of structural flexibility and substrate size. An example of latter in Lithographic manufacturing methods is the micro structural shapes production with special angles. For example with the exception of a 54.7° angle lithography methods can only produce binary perpendicular structures.

Diamond machining technologies provide a higher flexibility of geometrical shapes especially in the area of blazed grating units at a variety of angles. However the limited flexibility with regard to the structure orientation and modulation, long processing times are the problems in this method. Furthermore, in large area micro structured surfaces the difficulties in machining tolerances, influence dimensional accuracy. Thus, the design and manufacturing of optically functionalized elements is limited by the available manufacturing technology rather than optimal performance.

Another factor that plays significant role in current optical shape manufacturing is Surface Structuring methods in terms of high bandwidth, high accuracy positioning and motion control. One example of latter is State-of-the-art pick-and-place equipment, widely used in the areas of
surface mount technology (SMT) and printed circuit board (PCB) production. The accuracy of state-of-the-art SMT equipment and PCB production are in the range of +/- 10 μm that should be improved. Furthermore, substrate sizes, which can be processed with state-of-the-art equipment, are generally limited to about 500 x 500 mm².

As is discussed above, the micro structural surfaces state-of-art cannot fulfill the demands for new optical surfaces in terms of geometries and size and efficiency. Thus, there is need to new methods, which will discuss in next chapter.
4 Aim of the thesis

The flexible patterning of micro Structures using embossing technology will address these mentioned limitations of state-of-the-art micro machining technologies. As it is shown in this process optical structures will be manufactured directly into thermoplastic substrates using Adaptive Embossing Technology (Figure 4.1). Then the optical performance of this master substrate will be analyzed. At the next step an optimization algorithm will determine necessary optimizations on the substrate. This optimization rework will be repeated until the performance of the master substrate matches the design specifications. The final, substrate will then be used to produce a mould in order to replicate the structure. In this step galvanic processes will be optimized for the specific requirements of micro structure forming especially in large-area substrate sizes. Finally, these moulds will be used in high-volume replication processes of mentioned optically functionalized elements. For example they can be used in processes such as injection molding, injection embossing, or hot embossing.

This figure is omitted due to secrecy agreement

Figure 4.1. Motivation for flexible patterning of micro Structures using embossing technology, the focus of this work (red oval).

This work mainly deals with the step embossing process and specially design of the embossing head machine (Figure 4.1). The design is based on
the function of the whole embossing system, which is production of microstructure shapes on the optical substrate. The machine should supply the required functionality, which is needed in order to produce mentioned surfaces using embossing process. This work attempts to model and manufacture this machine, which will follow with experimental evaluation. In addition, the test bench of the embossing head will be assembled and the start up of the machine will be examined.

As is discussed the aim of the embossing head is to manufacture the optical micro structural shapes on the substrate. Here, the basic principle of step embossing system is discussed. In this system micro structured stamping tools will be used to print micro-structural elements into thermoplastic substrates (Figure 4.2). Each embossing tool features a uniquely designed optically functional structure. Then, a developed algorithm is used to calculate the exact location of the optical structures on the substrate, which can provide a high flexibility in production for a broad range of substrate sizes. In principle, this proposed patterning method that is based on a “pick-and-place” process has following steps. First, a stamping tool is picked from the tool tray with a manipulator arm. Second, the tool is being heated. Third, the manipulator moves the tool to the programmed location. Fourth, the tool structure is embossed into the substrate surface. Fifth, the manipulator moves the tool to the next location.

After embossing every programmed location for the specific tool, the manipulator moves the tool back to the tray and the process continues with the next tool in the same way. Thus, a substrate surface with varying structural pattern is produced. This process continues until the entire substrate surface has been printed with the respectively structured tools.

The structured tool area is situated on a flat surface, which has larger size than the tool size itself. This surface area will be provided controlled force.
for the depth of penetration of the actual embossing tool. This controlled 
pressure, is set low enough to not allow the outside surface to penetrate into 
the substrate, but high enough to imprint the heated tool geometry into the 
substrate surface.

The general aim of the embossing system in order to produce the micro 
structural shapes on the substrate was discussed in this chapter. In order to 
fulfill this aim at the first step the conceptual design of the embossing head 
according to the required functionality of machine is provided. In the next 
chapter this conceptual model will be discussed.
5 Conceptual & functional design of the embossing head

The adaptive embossing system needs a developed motion system providing high dynamics with micron positional accuracies. The overall machine concept of the adaptive embossing system is illustrated in (Figure 5.1). In this work the design of the stamping head (embossing head) is discussed.

One of the key complex modules of the production system is the stamping head mounting which provides the stamping motion, force control and tool handling, including alignment, mounting and temperature control.

The stamping head needs a fact interchangeable tool mounting system, precisely repeatable tool alignment and rigid mounting. For the stamping motion of the embossing head, a high bandwidth motion axis is used using a piezo, voice coil or direct drive motor. The actuator will be guided by a friction and stick-slip free system such as air bearings or flexure bearings.

Highly sensitive, high resolution force measurement devices such as load cells or strain gauges or force sensors will be used to provide the required highly accurate force feedback. The proposed motion system for the positioning of the stamping head consists of four degrees of freedom (DOF). High bandwidth x-axis and y-axis for positioning the stamping head at the programmed embossing positions on the substrate surface. In addition the regular z-axis for setting up the stamping head at a defined clearance to
the substrate surface. Additionally, a high bandwidth rotary axis in the xy-plane is required in order to change the rotary orientation of the embossing tool.

In order to achieve the required high bandwidth/high accuracy motion, some major factors such as high acceleration/deceleration, friction free motion, and high-resolution position feedback have to be considered.

In order to maximize force output in one hand and overall efficiency of the motion system in another hand high tech material with light weight should be use such as Carbon Fiber Reinforced Plastics (CFRP) or CFK. It is due to the fact that the acceleration and deceleration are directly dependent on the force output of the drive as well the size of the moving masses.

In this machine the vibration is produced by the acceleration. However, the vibration should be avoided as they interfere with the positioning accuracy of the system. Thus using a granite machine base is helpful in this case. A high mass ratio between the not-moving and moving masses is can reduce the vibrations. Furthermore, the granite itself has excellent material inherent damping properties. In addition, the granite can guarantee highest precision for the air bearings and linear axes.

Another factor, which is highly important in design of embossing head, is friction, especially when high bandwidth motion is also required. Thus a bearing system based on advanced air bearing technology such as vacuum supported self-loaded bearings should be used to provide friction-free motion, high stiffness and maximum design flexibility.

In addition to the described mechanical considerations for high bandwidth/high accuracy motion, a high-resolution measurement system is essential to provide the required positioning accuracy and repeatability. Advanced glass scale systems and laser interferometers like high accuracy encoders and sensors are suitable in this case. Beside the high resolution, special focus will be placed on the sampling rate, as it directly correlates to the achievable dynamics of the positioning system.

Knowing the general functionality of the embossing head the specifications and conceptual design of the three main factors of the machine will be discussed. These factors mainly classifies in three groups of linear motion system, Rotary motion system and embossing head tool set up.
1.1 Linear motion system

In this chapter the conceptual model of the linear system of the embossing head is discussed. The requirement factors like the stroke of the slider, the applying force at the tool head of the machine, the required velocity of the linear system are considered in this model. Different models are compared in terms of the position of the parts, the weight of the final model, mounting procedure and different components. However, selecting the parts will be carried out in detailed design of the embossing machine.

Based on the theoretical analysis of the machine, which is carried out by another group at Fraunhofer Institute, the required specifications of the linear motion are:

- Stroke: 10 mm.
- Stamping frequency: 10 Hz.
- Velocity: 0.63 m/s.
- Position accuracy: 0.1 µm.
- Stamping force: 10-50 N.
- Temperature range: 0-400°C.
- \( a_{\text{max}} > 80 \text{ m/s}^2 \).
- \( j_{\text{max}} > 10000 \text{ m/s}^3 \).

In order to fulfill above specifications of the linear motion system following components are required:

- Drive: voice coil.
- Measurement device: Linear encoder.
- Frictionless guidance device: Air bearings, granite slider.

Knowing the requiring specifications of the embossing head and using the previous models in Fraunhofer Institute following models are provided.
Figure 5.2. Conceptual design of the linear system of the embossing head (CorelDRAW). Torque motor position at the backside of the machine.

Figure 4.2 illustrates a conceptual model of the linear system, which focuses on the position of the voice coil as the drive of the motion. In this model the Torque motor is seated on the back side of the machine which rotates the whole parts including the voice coil. The voice coil provides the required stoke and force of the embossing head. In addition, appropriate cooling system should be design for the Torque motor and the voice coil. A slider with precision aluminum surface is used in order to provide smooth guidance of the linear motion. In addition, the air bearings, which are placed on the slider, provide the frictionless motion of the machine. The bearings air tubes path and the outlet are designed in the machine. The linear sensor is mounted on the inner housing of the embossing head which measure the linear motion. Since the embossing head will be mounted on the test bench vertically three holder edges are considered inside the inner housing in order to secure the position of the moving parts. These holders are placed at the start and end position of the slider stroke.

In this design since the aluminum slider is used the weight of the embossing head is less compared to granite slider in the next model. In addition the manufacturing of the aluminum slider is simple however; the rigidity of the aluminum is less than granite in terms of deformation and vibrations. In this model the holder edges are used which have simple mounting procedure. All the linear motion components rotate ±180 degree in this model by the torque motor, which is mounted at the end of the machine. The estimated overall weight of this model is 20 kg which is relatively lights compared to the other models.
Figure 5.3 illustrates another model of the linear system of the machine. In this model instead of the holder edges an anti-gravitational pneumatic cylinder is applied which utilizes a constant force. This cylinder is mounted at the back side of the machine which is connected to the moving parts using a connecting rod. This connecting rod is connected to the slider through the central hole of the voice coil. The other change in this model is using a granite slider instead of the aluminum one in the first model. In addition in this model the voice coil is mounted inside the rotor shaft of the torque motor. Both derive work in appropriate temperature using the cooling system and a thermal isolation at the end of the voice coil.

In this model the anti-gravitational cylinder provides a constant force during the linear motion which provides easier control of the linear drive force. In addition, since the voice coil is mounted at the rotor shaft of the torque motor the length of the machine is decreased in this model. However, a longer outer housing is applied in case which increases the overall weight of the machine in one hand and makes the complex wire path design inside the housing in other hand.

1.2 Rotary motion system

In this chapter the design of the rotary motion system of the embossing head is discussed. The requirement factors like the rotary range; the rotary accuracy and rotary speed of the rotary system are considered in this model. Different models are compared in terms of the position of the parts, the weight of the final model, mounting procedure and different components.
However, selecting the parts will be carried out in the detailed design of the embossing machine.

Based on the theoretical analysis of the machine, which is carried out by another group at Fraunhofer Institute, the required specifications of the linear motion are:

- Rotary range: +/- 180°.
- Rotary accuracy: +/- 2’’.
- Rotary speed: 20 Hz = 1200 1/min

This figure is omitted due to secrecy agreement

*Figure 5.4. Rotation of the housing (including the slider and four air bearing).*

In order to change the angle of the micro structural shapes on the substrate ±180° rotation is considered for the machine. This rotation applies to the linear system of the machine, which is mounted inside the inner housing (Figure 5.4).

This figure is omitted due to secrecy agreement

*Figure 5.5. Conceptual design of the rotary system of the embossing head (model 1).*

Figure 5.5 shows a model of the rotary system of the embossing head. In this model the torque motor is mounted at the backside of the machine and on a shaft. The rotation of the machine is provided using this shaft, which is
attached to the backside of the voice coil and inner housing of the embossing head. The position of the rotor is secured using a lock nut on the torque motor shaft. The back cover also secures the position of the stator on the outer housing. A rotary scanning sensor measures the rotation of the system. The scale of this sensor is mounted on the inner housing while the read head is attached to the outer housing. Two ball bearings which are mounted on the inner housing provide the frictionless rotation of the rotary system. The required shoulders and lock nuts are also considered in order to secure the position of the ball bearings.

The model above has simple mounting procedure especially regarding the wire path. However, the position of the ball bearings on the inner housing provides less stiffness for the rotary system. The overall weight of this machine is about 25 kg which is relatively heavy. In addition, the mounting procedure of this model is relatively easy.

Figure 5.6 illustrates another model of the rotary system of the embossing head. In this model the voice coil is mounted on the inner shaft of torque motor. The rotor is seated on the inner housing while the stator is mounted to the outer housing. The ball bearings which are mounted on the inner housing provide the smooth rotation of the system. A thermal sealing system is applied for the voice coil. The rotary sensor which measures the rotation of the system is mounted on the inner housing.

This figure is omitted due to secrecy agreement

*Figure 5.6. Conceptual design of the rotary system of the embossing head (model 2).*

In this model the outer housing cover the whole inner housing which causes a heavier machine however due to the position of the ball bearings the machine is more stable in term of vibrations. In addition due to big inner diameter of the torque motor a bigger derive should be selected that increase the weight of the machine over 20 kg.
Comparing these two models the position of the torque motor in the first model is preferred because it required smaller torque motor. In addition the position of the ball bearings in the second model is more efficient in terms of machine stiffness. However, due to difficult wire path design of these bearings seats both of the mountings will be considered in 3D design of machine in order to analyze them in more detail.

The final goal of the machine is emboss the optical micro structural shapes on the substrate which is carried out using above systems. Thus in the next chapter the design of the embossing head tool set up is discussed.

1.3 Embossing head set up

In this chapter the design of the embossing head tool of the embossing machine is discussed. The requirement factors like the applying force, force measurement accuracy, heating and cooling parameters are considered in this model. However, selecting the queried components of this set up will be carried out in detailed design of the embossing machine.

Based on the theoretical analysis of the machine, which is carried out by another group at Fraunhofer Institute, the required specifications of the linear motion are:

- Stamping frequency: 10 Hz.
- Position accuracy: 0.1 µm.
- Stamping force: 10-50 N.

Figure 5.7 shows the embossing head tool of the machine which applies the force on the substrate in order to emboss the optical shapes. A force sensor is also used in order to measure the applied force by the embossing head tool. This sensor is mounted on the top side of the embossing head. A heating system which is combined with a cooling system is also considered in order to melt the substrate in the first step and then cool it down. Using this way the optical shapes are embossed on the substrate surface and remain without change after the tool head leaves the surface. The design of the whole head tool set up is carried out by another group in Fraunhofer Institute. However, the results is used in order to be modeled the final assembly design of the embossing head.
Figure 5.8 illustrates the optimized conceptual model of the embossing head. In this model the torque motor is mounted at the back side of the machine. The position of the torque motor is secured using suitable lock nuts and covers. In addition a cooling design is considered in order to maintain the performance of the torque motor. A pneumatic cylinder is used in order to provide a constant gravitational force for the linear system. The granite is used as the slider material which provides a high finished surface and low thermal expansion (-2 µm/mk).

The linear encoder is mounted on the slider which detects the surface of the substrate in order to measure the distance between the head tool and the surface. This measured data will be used later by the control system in order to lead the voice coil. In other words the linear encoder detects the substrate surface before the embossing head tool touches the surface. Thus accurate distance of the slider stroke is measured which is required in leading of the linear system towards the substrate. In this model the position of this encoder is as close as possible to the head tool of the embossing machine in order to reduce the measurement error.

A sealing is considered for the ball bearings in order to protect the machine components against the grease leakage. However, this sealing design should be applicable for the situation that the outer housing is rotating while the inner one is fixed as this model.
6 Detailed design of the embossing head

In this chapter the detailed design of the embossing head is provided. The 3D design of the machine is modeled in Solidworks software. The focus of chapter is details of the embossing head components considering conceptual model and required functionality of machine. Thus the chapter consists of:

- Design of the parts which are manufactured by Fraunhofer Institute.
- To search the suitable parts and drives in different companies.
- To import the conceptual parts which should be bought from other companies and making the 3D model of them.
- To assembly the parts.
- To calculate the main specifications of final machine like Mass and moments of Inertia using Solidworks.

1.4 Linear motion system

In this chapter the linear movement of the embossing head is designed. The voice coil runs the slider and the head tool in order to emboss the optical micro structural shapes on the substrate. In order to have a controllable and smooth motion three main parts are designed which are drive, guidance components and measurement system. These parts are linked to each other by a robust control system. The detailed design of each part is provided in following chapters however; control group carries out the design of the control system.

Figure 6.1 shows the different parts of the linear motion system modeled in Solidworks according to conceptual model. At the backside of the slider the voice coil is mounted using suitable flange. The air bearings are places on the slider using the studs that utilize the smooth and frictionless movement of the slider. The linear sensor is mounted in middle of the slider in order to measure the stroke of moving components.
The scanning plate of sensor is glued on the slider while the read head of the sensor is placed on the housing. The detailed design of the linear movement of the embossing head is discussed in following chapters.

1.4.1 Measurement system

Since the penetration of embossing head tool in the substrate is in micrometer order, the stroke of slider should be very accurate. Thus a linear sensor is used to utilize a controllable movement for this linear motion. According to the conceptual model that the accuracy 0.1 micro meters is required a LIP type of linear sensor is chosen. The other required specifications have been checked and evaluated with this sensor model.

As it is shown in Figure 6.2 the LIP exposed linear encoders are characterized by very small measuring steps together with very high accuracy and repeatability. These sensors use the reflection of laser phase grating applied to a graduation carrier of glass ceramic or glass. They feature high accuracy and repeatability, and are especially easy to mount.
Knowing the required specifications of the embossing head and considering the conceptual model in latter chapter, the specifications of the chosen linear sensor (Heidenhain LIP 481) are [6]:

- Scale Accuracy: +/-0.5µm.
- Precision within one grating pitch: +/-1% of 4 µm = +/- 40 nm.
- Thermal coefficient of expansion of the scale: 0 µm/mK.
- Output signal: 1 Vss.
- Max. Speed: 7.6 m/min.
- Operating temperature: Up to 40°C.

There are some considerations, which should be taken into account regarding the mounting of the linear sensor. As it is shown in Figure 6.3 the distance between the linear head and scale is defined that is a critical point in terms of sensor performance. To simplify adjustment, supplier (Heidenhain) brochure recommends the following procedure:

1) To set the scanning gap between the scale and scanning head using the spacer foil.
2) To adjust the incremental signals by rotating the scanning head.
3) To adjust the reference mark signal through further, slight rotation of the scanning head.

Due to shortage of space inside the housing after assembling the air bearings on the slider, it is not possible to use the spacer foil in this case.

Thus an alternative mounting solution is provided which will be discussed in following chapter about the design and assembling procedure for read head mount of the sensor.
1.4.2 Drive system

In this chapter the procedure of drive selection is discussed. As it mentioned in conceptual model due to the required high accuracy of linear motion of embossing head a highly controllable drive is needed. In addition, due to shortage of space inside the machine the drive should be relatively light and small. Thus a voice coil is chosen which can fulfill these requirements.

Voice-coil actuators are electromagnetic devices, which produce accurately controllable forces over a limited stroke with a single coil or phase. They are also often called linear actuators, a name also used for other types of motors. A related form is the swing-arm actuator, which is used to rotate a load through a limited angle (usually 30 degrees or less) [9].

These devices are capable of extremely high accelerations (more than 20 times gravitational acceleration, or "g"), and great positioning accuracy when highly controlled (one millionth of an inch or better). A properly designed device may have a settling time (the time required for structural vibration to settle down to below the measurement threshold after a high-acceleration move) of two milliseconds or less. The major use of this type of actuator is in computer disk drives. They are also used in shaker tables, lens focusing, medical equipment, laser-cutting tools and elsewhere.

In order to choose a voice coil following calculations are done using supplier Handbook [9]:

Following the Peak force equation gives,
\[ F_p = F_l + F_f + F_m \]  \hfill (6.1)

Where,

- \( F_l \) is the constant load force which considered to be zero because the pneumatic anti-gravitational cylinder (Airpel) is utilized that provides constant force during the stroke.
- \( F_f \) is the friction which considered to be zero in this step of design.
- \( F_m \) is the acceleration of mass

Assuming the triangular velocity profile and knowing the average speed of embossing head form conceptual model the maximum speed of the head is calculated as follows,

\[ V_{MAX} = 2 \times V_{TRI} = 2 \times (0.63) = 1.26 \, \text{m/s} \]  \hfill (6.2)

Knowing required frequency, the period can be derived as followed,

\[ f = 10 \, \text{Hz} \Rightarrow t = \frac{1}{f} = 0.05 \, \text{s} \]  \hfill (6.3)

Thus the acceleration is calculated as follows,

\[ a = \frac{V_{max}}{t} = \frac{1.26}{0.025} = 50.4 \, \text{m/s}^2 \]  \hfill (6.4)

Knowing the moving mass \( M_\alpha \) using the measuring toolbox of Solidworks and using the latter equation gives,

\[ F_m = m_\alpha \times \alpha = 3.1 \times 50.4 = 156.24 \]  \hfill (6.5)

Knowing the required embossing force from the conceptual model gives,

\[ F_e = 10 \, \text{N} \]  \hfill (6.6)

Thus the total force becomes,

\[ F = 206.24 \, \text{N} \]  \hfill (6.7)

Choosing the safety factor of 2 yields,
F = 412.48 N

Knowing the peak force, continuous stall force, Total stroke (25 mm) and considering the available space inside the housing a suitable voice coil is chosen from the brochure of company.

The specifications of the chosen voice coil (LA30-43-000A) are:

- Stroke: 25.4 mm.
- Peak force: 444.8 N.
- Continuous force: 185 N.
- Length: 112.27 mm.
- Outer Diameter: 76.2 mm.
- Weight: 2.7 kg.

Figure 6.4. Voice coil (Beikimco), LA30-43-000A (Source: Beikimco Brochure)

Figure 6.4 shows the dimensions of the chosen voice coil (LA30-43-000A). These data is used in order to model the voice coil in Solidworks software. The position of the screw holes on the moving part of the voice coil is not adaptable to the slider. Thus, an adapter plate is designed in order to mount the voice coil to the slider and other moving parts. The design of this adapter plate is discussed in chapter 1.7.3 Flanges (Adapter plates).
addition, a new set of screw holes and sinkings are drilled on voice coil in order to reduce the size of the adapter plate.

1.4.3 High precision guide system

In this chapter the selection and mounting system of air bearings are discussed. Air bearings utilize a thin film of pressurized air to provide a ‘zero friction’ load bearing interface between surfaces that would otherwise be in contact with each other (Figure 6.5). Being non-contact, air bearings avoid the traditional bearing problems of friction, wear, and lubricant handling, and offer distinct advantages in precision positioning and high speed applications.

The fluid film of the bearing is achieved by supplying a flow of air through the bearing face and into the bearing gap. An orifice or a porous media that restricts or meters the flow of air into the gap typically applies this film. The restriction is designed such that, although the air is constantly escaping from the bearing gap, the flow of pressurized air through the restriction is sufficient to match the flow through the gap. It is the restriction through the gap, R2 that maintains the pressure under the bearing and supports the working load. If air pressure were introduced to the gap without restriction (R1), the flying height would be higher, the air consumption higher, and the stiffness would be lower than could be achieved with proper restriction. This restriction is referred to as air bearing compensation [8].

Since the accuracy of the head tool is in the order of 0.1 micro meter and the force needed for embossing is 50 N the static stiffness is calculated which is 500 N/µm. However, due to vertical position of embossing head on the test bench the weight of the moving parts is not considered in carrying capacity of the air bearings. In addition, due to shortage of space
inside the housing, the size of the bearing has been considered. Using the air bearing handbook [8] and knowing above specifications following air bearing is chosen.

### Table 6.1. Selected rectangular air bearing specifications.

<table>
<thead>
<tr>
<th>Specification</th>
<th>Unit</th>
<th>Model 1</th>
<th>Model 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air supply pressure</td>
<td>bar</td>
<td>5</td>
<td>6</td>
</tr>
<tr>
<td>Maximum carrying capacity</td>
<td>N</td>
<td>12350</td>
<td>14570</td>
</tr>
<tr>
<td>Nominal carrying capacity</td>
<td>N</td>
<td>9100</td>
<td>10740</td>
</tr>
<tr>
<td>Gap height</td>
<td>µm</td>
<td>5.8</td>
<td>5.8</td>
</tr>
<tr>
<td>Static stiffness</td>
<td>N/µm</td>
<td>1080</td>
<td>1280</td>
</tr>
<tr>
<td>Air consumption</td>
<td>N/µm</td>
<td>4.6</td>
<td>5.5</td>
</tr>
<tr>
<td>Size W, L, H</td>
<td>mm</td>
<td>120, 240, 70</td>
<td></td>
</tr>
<tr>
<td>Bearing weight</td>
<td>g</td>
<td>5000</td>
<td></td>
</tr>
<tr>
<td>Thread air supply</td>
<td>G</td>
<td>1/8</td>
<td></td>
</tr>
</tbody>
</table>

However, there is restriction regarding the available space inside the inner housing. Thus the efficient shape for the air bearing would be rectangular compared to circular pads considering the location of air bearings on the granite slide. (Table 6.1) shows the specifications of the chosen air bearing. Using this air bearing the required carrying capacity is fulfilled. Furthermore, the dimensions of the air bearing are well suited for our model concerning the shape of the slider.

Figure 6.6 shows the suitable mounting design of air bearings inside the housing considering the conceptual model. Although, the design has higher roll stiffness the bearings are not directly across from each other it can be difficult to separate angular adjustments from roll adjustments. Furthermore due to shortage of space inside the housing we need to make the bearing studs as close as possible to each other.
Another part involved with the guidance of the linear motion is the slider. This part in one hand connects the voice coil to the head of machine and in other hand provides smooth surface for the frictionless movement. In addition, due to the high accuracy of embossing system it is needed to have no deformation in the shape and characteristic of the parts specially the slider. Thus the granite is used as a martial of the slider in order to fulfill these required specifications.

In addition, high machining capability of granite makes is suitable in terms of finishing and grinding that is needed for such a precision machine. Furthermore, since using the air bearings a very smooth surface is needed in order to provide a thin air layer for the air bearings. However, there are some limitations regarding granite as the base material of slider. First, since drilling the granite is problematic, mounting the other parts on the granite is not simple. Thus, according to granite standard [2] in first step, the holes are drilled on the slider, which will be used later in order to glue a thread insert inside them. This thread will be used for mounting screws of other parts on the slider. This mounting process of granite makes the diameter of the holes on the slider bigger compared to needed screws. Consequently, the size of the slider increases which causes a heavier machine.
Figure 6.7 illustrates the design of the screw holes is a critical step in the slider design. According to Granite standard, minimum thickness of material should be 3 mm. Thus in design of slider the distance between holes and other sides should be at least 3 mm. However, in order to reduce the mass this thickness should be as small as possible. Thus, during the slider design the model should be optimal in terms of lightness and minimum thickness. In addition, knowing that two flanges are used at both ends of slider, the diameter of slider central hole also should be optimized.

The holes on the long side of slider are used to mount the length gauge, which is the sensor to detect the substrate surface smoothness. First step in designing of these holes is to choose the suitable screws for the gauge clamping sleeve. The design of the clamping sleeve will be described later, but the results are used here to choose the diameter of holes. Knowing these data, the length Gauge holes are for M3 screws which have the diameter of 6 mm and the depth of 15 mm (according to granite standard).

1.5 Rotary motion system

As it defined in the conceptual model of the embossing head the head tool should provides a 180-degree rotation in each directions in order to emboss the optical shapes on the substrate in different angles. In order to provide
such a rotation three main systems are designed which are measurements system, drive and frictionless guide system (Figure 6.8). The detailed designs of these components are provided in following chapters.

This figure is omitted due to secrecy agreement

Figure 6.8. Rotary motion components (Solidworks).

1.5.1 Measurement system

As it defined in the conceptual model of the embossing machine the head tool needs a +/-180° rotation. Thus a rotary sensor has been used in order to measure the required rotation generated by torque motor. In order to select a suitable rotary sensor there are some characteristics that should be considered. The first one is the required accuracy of the rotary sensor which is +/-3” per revolution. The second specification, which is crucial, is the dimensions of the sensor considering the shortage of space inside the housing.

The mounting procedure of the sensor is another factor that should be adapted to the conceptual model. In addition the sensor place should be far enough from the heat sources like torque motor or voice coil.

Knowing the motioned points the RESM rotary encoder with following characteristics had been chosen:
Renishaw Signum RESM

- Accuracy per revolution: +/-1.94°.
- Outer diameter of the ring: 115 mm.
- Maximum Speed: 2075 rev/min.
- Output signal: 1 Vss.
- Operating temperature: Up to 85°C.
- Weight of the ring: 0.25 kg.

Equally important, RESM low mass, low inertia design does not compromise system performance.

![Diagram of RESM rotary encoder](Signum RESM brochure)

**Figure 6.9. RESM rotary encoder (Source: Signum RESM brochure)**

As it is shown in figure 6.9 the relative dimensions of rotary sensor and the scanning scale should be 0.8 considering required tolerance. The minimum angle of the sensor wire also is defined in this figure, which should be considered in mounting design of the machine in terms of available space. In addition, two sets of screw are shown in this figure, which the ones on
top of the scanning read head are used in our model. Because using these screws the scanning read head can be mounted on the outer housing of the machine. The mounting procedure of the rotary encoder needs some considerations, which are discussed in assembly chapter of this thesis. The other important consideration regarding the mounting design of the read head of the sensor is the LED setup. This screen shows the temperature of the sensor in every moment, which is important in terms of sensor performance. Thus, in design of the mount seat of the sensor on the outer housing visibility of this screen should be considered.

As it discussed before the accuracy of the rational movement of the embossing head tool is important concerning the angle of optical micro structural shapes. Figure 6.10 shows the comparison of the sensor accuracy and the width of the tool head. In other words, the error at the outer diameter of the head tool had been compared to the error due to the accuracy of the rotary sensor.

![Figure 6.10. Rotation accuracy at the outer diameter of the nickel shim (Δ) compared to sensor accuracy (Δε).](image)

Since the required accuracy at the head tool is dependent on its radius, the accuracy change due to different radius is plotted in figure 6.11. However, it should be considered that the required accuracy for the head tool is one micro meter which is shown with black line. Thus the accuracy of the sensor should be more than the relative accuracy for the applied tool head radius.
1.5.2 Drive system

In order to provide the rotary movement for the embossing head a direct drive motor is used. A DD motor is a servo actuator which can be directly attached to the load which increases servo motor stiffness. Direct drive motors are well suited to applications where a minimized size, weight, response time and required power input is desired, while maximizing positional accuracy. These frameless motors require some consideration with respect to torque sizing and installation [11].

Series Frameless Direct Drive Rotary (DDR) motors utilize a neodymium-iron magnet rotor structure and use armature assembly to provide smaller levels of torque/volume. The windings are provided with high temperature epoxy, which provides excellent thermal properties and mechanical protection.

Encoders are feedback devices usually mounted on the brushless motor axis. One or more of these, in addition to current sensors, are used to provide the position and velocity feedback to the amplifier (Current sensors are built into the amplifier). Position loops, which can use an encoder, require special amplifier and system configurations.

Generally, a frameless brushless motor consists of three components: the armature assembly, the field assembly, and a position sensing device. The
The stator or armature assembly is the outer, wound member and is stationary. It consists of lamination material formed into a core with slots that are either straight or skewed. The windings consist of a series of copper coils for each motor phase. Phase interconnections are made inside the winding, and leads are brought out for connection to an amplifier (figure 6.12).

![Image](https://via.placeholder.com/150)

*Figure 6.12. Torque motor components (source: ETEL Handbook).*

The rotor or field assembly is the second component of a brushless motor and is the rotating member. It typically consists of permanent magnets. Magnet materials available include samarium cobalt and high-energy neodymium-iron-boron compounds. Magnets are mounted around the outside of the rotor (figure 6.12).

In order to choose a suitable torque motor following parameters should be considered. The required specifications of the conceptual model like maximum speed, continues torque, peak torque type and dimensions of torque motor, which are the input data for selecting a suitable torque motor. In addition, the other characteristics of the chosen torque motor like temperature range, number of poles and volume/torque should be checked to the conceptual model.

To estimate the required torque of the embossing machine following equation are used using the supplier handbook [11].

\[
T = J\alpha + T_f
\]  
(6.9)

\[
T = \frac{JN}{C_4 + t} + T_f
\]  
(6.10)
Where,

- $T$ is required torque
- $T_f$ is friction torque
- $N$ is required RPM
- $C_4$ is unit conversion factor
- $t$ is acceleration time
- $\alpha$ is acceleration

Since there is no external load regarding the rotation of the machine the required torque is calculated as follows.

Knowing the frequency of rotation from conceptual model and estimating the preliminary diameter of the machine, the RPM is calculated as follows,

$$f = 20 \text{Hz}$$  \hspace{1cm} (6.11)

Knowing the estimated diameter of housing, required RPM is derived as follows,

$$\Rightarrow RPM = 1200$$  \hspace{1cm} (6.12)

Using measurement program inside the Solidworks software the Moments of inertia of the preliminary model obtained as follows (considering the X direction along the cylinder at the center of mass),

$$I_{yx} = 2.5 \times 10^{-3} \frac{kg}{m^2}$$  \hspace{1cm} (6.13)

Since a super precision ball bearing is used in order to provide the frictionless guidance for the rotary motion of machine, the friction torque is considered to be zero. The detail design of this ball bearing will be provided in following chapter.

Considering the unit conservation factor for N-m and using equation (7.10) from supplier handbook gives,

$$T = 1.3Nm$$  \hspace{1cm} (6.14)

Applying the safety factor of 3 gives,
Using the Handbook of the supplier (Danaher Company) the Kollmorgen F/FH (high voltage) from frameless Direct Drive Rotary (DDR) motor series is selected which can fulfill conceptual model requirements. The model F/FH4305 has following specifications,

- Peak torque: 16.9 Nm.
- Continuous Torque: 5.48 Nm.
- Thermal Resistance: 0.831 °C/W.
- Number of poles: 16.
- Total weight: 1.9 kg.
- Inertia: 13.04*10^-4 kgm².
- Dimensions = 160, 76 and 37 mm.

This motor is suited for application which minimized size and weight are desired while maximizing positional accuracy. In addition, since the machine needs relatively slow speed, this motor can provide smooth low-speed rotation without Low cogging. Furthermore, Windings encapsulated with high temperature epoxy for high thermal transfer and mechanical protection. In addition, by adapting the machine directly to load the machine its size and weight decreases. Furthermore, in this model the number of poles is high (16) which provide smoother rotation of machine especially in this case where accurate position is needed.

In order to design the housing of the torque motor some considerations regarding the stator housing as well as the rotor and shaft adapter should be considered (figure 6.13). As it is mentioned in Kollmorgen Handbook [9] the housing structure must be strong enough to support the stator so no distortion occurs.

In the first step since the housing material for a rare-earth magnet motor should be nonmagnetic and also light in this case, Aluminum is selected as base material of the housing. In addition, three methods are offered by Kollmorgen Handbook [9] utilized for securing the stator into the housing. It can be clamped in place using a clamp ring, an end bell, or the stator may be bonded into place (Figure 6.13). However, in this machine the bonding solution with additional clamp is used.
In next step the mounting of the rotor on the shaft is determined. As it is offered by Kollmorgen Handbook [9] the rotor is secured by bonding it to a shaft, clamping it in place, or holding it with a shrink ring. Bonding the rotor to the shaft is the most common method. When bonding the rotor, the shaft diameter tolerance should be held to 0.03 - 0.05 mm below the minimum rotor diameter. In the embossing head design instead of shrink ring a lock nut is used on the shaft to secure the position of the rotor; however the bonding method is also used.

In order to determine and secure the rotor to the shaft, the rotor must be positioned axially. In this machine a shoulder on the mounting shaft is designed in order to bank the rotor against this shoulder when mounted on the shaft. However, it should be considered that the outside diameter of the axial locating shoulder should be kept below the bottom of the magnets. In addition, there is a mounting requirement shown in (figure 6.13) which is crucial in modeling of the machine in terms of torque motor performance.

In design of embossing head to achieve the mentioned mounting requirement a distance ring is used. In other words, it is more efficient to manufacture the tolerance on this distance ring instead of the of torque motor shaft. To follow this procedure has some following benefits in design
and manufacturing of the embossing machine. First, it is easier to mount all the torque motor shaft components on the shaft first and then measure the distance between the edge of stator in order to manufacture the distance ring with suitable tolerance. Second, in case of any measuring mistake it is easier to remanufacture the distance ring, which is the smaller part, compared to the shaft.

Another parameter that should be checked is the temperature range of torque motor, which is controlled by a temperature sensor. The supplier company installs this thermistor on the Torque motor.

1.5.3 High precision guide system

As it discussed in pervious chapters in addition to linear motion the embossing machine requires a rotation in order to emboss the micro structured shapes in different angels on the substrate. Thus a frictionless guide system is required in order to supply the rotational movement for the rotary movement system. Consequently, a spindle bearing is selected by another group in Fraunhofer Institute although; the design of the mounting procedure is carried out in this project.

The specification of the selected spindle bearing which is a double row high precision bearing (719 USS 110) is provided [15].

- Dimensions: D= 150 mm, d= 110 mm, B= 20 mm.
- $C_0 = 62000$ N, (static load rating).
- C=55000 N (dynamic load rating).
- Speed limit (RPM) for Grease lubrication= 7000.
- Mass= 0.85 kg.

As it discussed in the conceptual design the air bearings should be mounted on the CFK housing which has $+/-180^\circ$ rotation. In order to provide a stable design one set of the bearings is located at the end of the CFK housing and the other set at the end side of outer housing (Figure 6.15). A ring which is glued to the CFK housing is considered to secure the position of the right ball bearing. There are also two rings between two bearings which they bank against these reigns. The left ball bearing is secured by tow lock nuts. The upper one will be mounted on the inner surface of the outer housing and the down nut is screwed on the threaded surface of the adaptive plate.
There are some mounting factors which are considered in this model. First, there is small gap (0.5 mm) between the distance rings and the housings (Figure 6.15), which is shown by red oval. This gap utilizes the easy mounting process of the ball bearings over the CFK housing in order to move them to their positions. However, on the seat position of the ball bearings on (CFK housing) a suitable tolerance is considered in order to bond the ball bearing on the housing. Second, regarding the left ball bearing a gap is considered on the outer housing shoulder in order to prevent double fitting of lock nuts and outer housing.

![Figure 6.15. Design of ball bearing mounting procedure (Solidworks).](image)

Considering the design elements that mentioned above, the mounting procedure of the ball bearing has five main steps. First, the holder ring is glued in order to secure the position of right bearing. Second, the ball bearing at the right side is banked against the outer housing shoulder and the ring. Thirds, the distance rings are mounted between two ball bearings. Fourth, the left ball bearing is bonded on the CFK housing and is banked
against the distance rings. Finally, the position of the ball bearings is secured using the lock nuts.

In previous part one mounting design of the ball bearings were discussed which use the end side of the outer housing and CFK housing as seating position of the bearings. Here another mounting model of the ball bearings is discussed. The main modification in this design is based on the position of the ball bearings. In the first model, the positions of the ball bearings are close together. This is due to the reason that top area of the CFK housing is the mounting position of different components like: linear read head, air bearing studs, cable exits and wire clips. Thus, this shortage of space makes it difficult to mount the ball bearing on this area of the CFK housing.

In the second model, the main modification is optimization of ball bearing mounting position. In other words, the two ball bearings are at the both sides of the outer housing which required the increasing of outer housing length. Using this design has some advantages and also some disadvantages which are mentioned here (Figure 6.16).

• The first model is easier in terms of mounting of the embossing head components.
• The second model is lighter due to shorter outer housing.
• The wire path for the sensors and air supply tubes of the air bearings easily can be extracted from the CFK housing using the holes (thread insert)
• The second model is more stable due to the positions of the ball bearings.
• The second model is more rigid in terms of vibrations and rotational movements.
• The second model is more difficult to design and manufacture.
• The demounting of the components in the second model is harder in term repairing and maintenance.

Although the first model is easier to design and manufacture, after consulting with other groups, the second model has been chosen. Since, the accuracy of the machine should be high the model should be rigid enough to supply this requirement.

There are some factors which are considered in design of the distance rings between two bearings which secure the position of the bearings. In addition
to the functionality of these rings the mounting procedure possibility of the whole assembly should be considered. For example the nuts of the air bearing studs which are mounted on the CFK housing had interference with these rings. At the first step these contact areas were detected using the interference option in Solidworks software. Then using appropriate holes and cuts the positions of air baring studs were provided. Furthermore four holes were cut on the rings and the CFK housing in order to check the position of the slider inside the housing during assembly process. In other words, in order to centralize the slider inside the housing the position of the slider should be measured in four directions. This measurement is carried out using linear encoders. Thus in orders to provide the access to the surface of the slider after assembly these holes are cut on the ball bearing rings.

In design of the distance rings the thickness of them should be big enough to stand the bearings force. However, the inner ring should hold the inner rotary ring of the spindle bearing while the outer ring should be banked against the fixed part of the bearing. In addition, in assembly process of the embossing head the mounting sequence of the spindle bearing set up should be considered. In other words, this process should starts from the top of the machine. First, the right bearing is banked against the shoulder of outer housing. Then using two distance rings the position of this spindle bearing is fixed. In the second step the other bearing is banked against the distance rings. Finally the position of the spindle bearing set up is secured using the lock nuts at the bottom of the machine.

In addition, mounting the spindle bearings is carried out using bonding process. Thus, the bearings should be warm up before mounting them on the CFK housing. However, due to difficulties of the CFK cutting process, tolerance manufacturing of the inner housing is critical. Thus, appropriate modifications in the applied tolerance should be utilized after preliminary manufacturing of the CFK housing.

In this chapter rotary system of the embossing head was provided which consists of drive system, measuring system and frictionless guide system. In the next chapter the embossing head tool design of the embossing head is discussed.
This figure is omitted due to secrecy agreement

*Figure 6.16. First and second model comparison (Solidworks).*
1.6 Embossing head tool set up

The goal of the embossing machine is to emboss the optical micro structural shapes on the substrate. The head tool of the machine is designed in order to fulfill this purpose. The head tool consists of a ceramic heater, vacuum system and cooling system. The heater melts the substrate in order to emboss the micro structural shapes on it. However, the surface of the substrate should be cool down fast in order to prevent unwanted deformation. The vacuum system is used in order to provide a pick-and-place motion of the head tool from the head tool tray to the substrate place. However, the design of the head tool system is carried out by another group and the results is used in this project in order to design the embossing head tool set up.

This figure is omitted due to secrecy agreement

Figure 6.17. Embossing head tool components (Solidworks).

Figure 6.17 shows the components of the embossing head tool. The linear encoder detects the surface of the substrate in order to find the exact distance of the head tool and substrate surface. This data is used by control system in order to lead the voice coil drive. This sensor is mounted on the slider using a sleeve clips. A force sensor is also used in order to measure the applied force and provides a controllable applying force. This sensor is mounted on the slider using an adapter plate. The detailed design of these parts is discussed in following chapters.
1.6.1 Force sensing system

In order to have the controllable and accurate applying force to the substrate in manufacturing the micro functional optical shapes, a force sensor is used. A force sensor generally measures the applied force from the proportional deformation of a spring element. The data generated by this sensor can be used by control system to lead the voice coil as the drive. The position of force sensor is between the tool head and the slider flange.

These press force sensors are based on the piezoelectric measuring principle. The force acting on the quartz element generates at the output of the sensor a proportional electric charge, which is converted by the measuring amplifier into a process signal suitable for evaluation. One of the important factors for this sensor is rigidity. Since the penetration of embossing head is in order of micro meter, the high rigidity of force sensor is needed.

The flange connections at both ends allow flexible mechanical adaptation of the sensor to provide the particular machine model. The included centering rings also utilize axial adjustment. The rotationally symmetrical shape of the press force sensor makes it suitable for mounting on the end of connecting rods [18]

Figure 6.18. Calibrating element with force distributing cap, flange and cable protector (source: Kistler brochure).

Knowing the required force specifications and dimensions from the conceptual model the sensor Kistler 9323A with following specifications is selected.

- Rigidity: 1410 N/µm.
- Natural frequency: ≥74.5 kHz.
- Sensitivity temperature coefficient: 5% C.
• Bending moment Mx,y, max: 0.9 Nm.
• Shear force Fx,y, max.: 0.62 kN.
• Operating temperature range: –40-120 °C.

1.6.2 Surface detection system

Due to the high accuracy of embossing process (0.1 micro meters), the surface of the substrate should be highly smooth. However, due to relatively big size of the substrate makes it difficult to manufacture in terms of micro meter order. Thus a linear encoder is used in order to detect the substrate and measure the distance between head of the embossing machine and substrate. This data will be used by control system in order to lead the voice coil to the required penetration depth in the substrate.

In order to utilize this required detection a linear encoder is used. The components of the encoder are shown in Figure 6.19. The scanning head with a light source scan the reflected light from the scanning graded plate in order to measure the displacement. The length gauges have a defined thermal behavior.

Figure 6.19. Design of linear encoder (Source Heidenhain Brochure).
Since temperature variations during measurement can result in changes in the measuring loop, the linear encoder uses special materials with low thermal coefficients of expansion for the components of the measuring loop. This keeps the functionality of the sensor in a relatively large temperature range.

In order to choose a suitable sensor for our machine there are some main factors that should be considered. The first one is the accuracy of the sensor which should be less than 0.1 micro meters. In addition, according the conceptual model the required measurement range of the embossing head is 12 mm, this should be utilized by encoder. The second factor is the size of the linear encoder. As it is mentioned in conceptual model the sensor should be as small as possible regarding the weight and size.

In addition to mentioned characteristics of the sensor the position of the encoder and mounting procedure is critical. In other word, the purpose of this encoder is to measure the position of the embossing point on the surface of substrate. Thus, it is important for the sensor to close to the head tool of the machine. As it is shown in the (Figure 6.20) the model at the right has closer position to the head of machine and can consequently have more accurate data for the embossing process. However the right model is more difficult in terms of modeling, manufacturing and design the mounting procedure.

Furthermore, the possibility of mounting of the sensor should be checked and a suitable clamp should be designed in order to mount the linear encoder on the Granite slider. Another factor considered in this step is the required space of the cable path inside the housing and allowed bending radius of it. In addition, the distance (6 mm) of the tip of the encoder to the head of the machine is determined according to sensor stroke which should be also considered in our design. Knowing the required characteristics of the measuring system and considering the conceptual model, the pneumatic Heidenhain MT1271 (ST 1277) encoder with following specifications is selected [6].

- Scale Accuracy: +/- $1\mu$m/12mm ( +/- $1\mu$m/12mm).
- Precision within one grating pitch: +/-1% of 4 µm (20 µm) = +/-0.04µ-0.2µm).
- Thermal coefficient of expansion of the scale: 0 µm/ mK.
- Maximum Speed: 0.5 m/s.
Operating temperature: Up to 40°C.
Weight: 0.110 kg.
Pneumatic drive.

Figure 6.20. Comparing different mounting position of linear encoder.

The alignment of the encoder, relative to the slider is utilized using set of gauge blocks. In other words, the surface side of the slider and the sleeve clamp will be used in assembly procedure in order to paralyze them using the gauge blocks.

1.7 Mechanical components

In previous chapter the main systems of the embossing head is discussed. In this chapter the design, mounting procedure and modeling of the mechanical components are provided. The parts are classified mainly in seven groups which are torque motor shaft, torque motor cooling system, flanges, linear sensor mount, air bearing mount, housing adapter plate and sealing parts.
Figure 6.21. Mechanical components of the embossing head (Solidworks).

Figure 6.21 shows the mechanical components of the embossing machine. In this figure the CFK housing is provided as a transparent part in order to provide better presentation of the 3D model. At the front side of the machine the position of the sealing part is shown. This sealing prevents the dust and dirt to enter the inside space of the machine that can influence the performance of the sensitive parts like sensors. The detailed design of the mentioned parts is discussed in the following chapters.

1.7.1 Torque motor shaft

Torque motor shaft is the part that transmits the rotary motion from the torque motor to other rotary parts. This part is one hand is attached to back side of voice coil and in other hand attached to the CFK housing which provides the rotation for both parts. The parts and components that are mounted on this shaft are: Torque motor, rotary sensor, Pneumatic cylinders for supplying constant gravitational forces (Airpel), and lock nut. As mentioned in design of the torque motor shaft, the goal is to transfer the
rotation to head of the embossing machine. In addition, the mass of the shaft tried to be as small as possible in order to reduce the total mass of the machine.

Figure 6.22 shows the seat position of the parts which are mounted on the torque motor shaft. The screw holes are designed according to the voice coil holes and required screws. At the center of the torque motor shaft the Pneumatic cylinders for supplying constant gravitational forces (Airpel) is attached. The rotary sensor seat has designed according to the sensor mounting procedure. A lock nut with the threaded surface inside also is mounted on the shaft in order to secure the position of the torque motor on the shaft.

In above figure the two shoulders are designed in order to mount the rotary sensor scale and the CFK housing against them. In other words the required screws for mounting of these components on the torque motor shaft are mounted on these shoulders. In order to reduce the size and mass of the torque motor shaft these two shoulders are combined together (Figure 6.23). However, suitable sinkings for the head of the CFK mounting screws
is designed in order to provide the mounting place of the rotary sensor scale on the shaft. Thus, using this modification, the weight of the torque motor is decreased. However, in assembly process of the machine the mounting sequence of the components on the torque motor should be considered. In other words, fist the torque motor should be mounted to the CFK housing on the mentioned shoulder then the rotary sensor scale can be banked against this shoulder.

Knowing the specifications of every part on the shaft and considering the conceptual model the mounting procedure of the mentioned parts on the torque motor shaft is provided. Fist, the torque motor is mounted on the backside of the voice coil. Second, the scale of the rotary sensor is mounted on the shaft. Third, the cooling ring of the torque motor is banked against the outer housing shoulder. Fourth, the stator is banked against the cooling ring. In the fifth step, the mounting requirement of the torque motor should be performed. Thus the distance between upper edge of the stator and the rotor is measured. Then the distance ring is manufactured according to the latter measured distance and is seated to the side of the designed shoulder of shaft. Sixth the rotor is banked against the distance ring. Seventh, mounting the lock nut to the backside of the rotor the position of the whole torque motor assembly is secured. Eighth, the Airpel and connector rod is attached inside the shaft. Finally the back cover is used to seal the backside of the embossing head.

This figure is omitted due to secrecy agreement

Figure 6.23. Backside components of embossing machine (Solidworks).
There are some considerations that are taken into account during the design of torque motor shaft and components. First, in order to prevent from double fitting in back cover, there is small cap (0.5 mm) between back cover letter and outer housing. Because, the back cover should only bank against the stator (Figure 6.23). The same gap is designed between the lock nut and the shoulder of the torque motor housing. Second, there some chamfer and fillets applied in this part. For example, the 15-degree chamfer at the edge of outer housing is designed according to O-ring Simrit handbook [13]. This chamfer provides a safe and easy mounting procedure for the cooling system and O-rings against the edge of outer housing during the assembling of the embossing machine.

1.7.2 Torque motor cooling system

In this step the cooling design of the torque motor is discussed. The cooling channels are machined on the frame of the stator enable the water circulation to dissipate the heat that results from power losses in the winding. Dissipation of the heat allows the motor to maintain a higher continuous torque than an uncooled motor. The cooling channels are sealed in the outer housing with two O-rings.

![Figure 6.24. Cooling system (Source: ETEL handbook).](image)
In manufacturing process of the cooling channels, the water-cooling inlet and outlet must be aligned with the output cables (strain relief) to guarantee proper cooling (otherwise the surface of torque motor is not cooled equally) (Figure 6.24). In addition to the inlet/outlet of the water cooling system, an extra outlet is considered at the bottom of the torque motor housing in order to extract the water from the system.

As it is shown in set of parallel channels are used in order to circulate the lubricant (Water in this case). Considering the conceptual model this cooling system is applicable to the embossing head according in terms of size and cooling procedure. However, the design of outer housing should be adapted to this system in terms of space availability and mounting procedure.

![Diagram](image)

*Figure 6.25. The circulation of water in cooling system (Source: ETEL handbook).*

As it is shown in Figure 6.25 the water enter the channel through water-cooling inlet and after passing all the surface channels leave the system from water-cooling outlet. In addition, the water can extract form the cooling system through the outlet which is designed at the bottom side of the cooling system in the case of maintenance or repair.

In order to design the cooling system the ETEL handbook of torque motor [12] and previous cooling system design of a machine in Fraunhofer institute are considered. In design of the cooling system the dimensions offered by the ETEL handbook are adapted to the embossing machine in terms of outer housing geometry, torque motor type (considering the previous design in institute) and the poison of the torque motor inside the embossing machine.
Thus, using the offered channel dimensions by ETEL handbook for the model F/FH4305 and adaptation to the embossing machine following values for the cooling system channels are used.

\[ X = 6 \text{ mm (Axial direction)} \]

\[ Y = 5 \text{ mm (Vertical direction)} \]

Figure 6.26 shows a similar sealing design to the embossing head machine which is offered by Simrit O-ring Handbook [13]. The direction of the pressure is shown here which represents the water pressure of the cooling system.

![Figure 6.26. O-ring design of the cooling system (Source: Simrit Handbook).](image)

Using conceptual model and knowing the diameter of the selected torque motor and designed housing as \( d_7 \) and \( d_8 \) following dimensions for O-rings are selected:

\[ D = 169.5 \text{ mm (diameter of the O-ring)} \]

\[ d = 3 \text{ mm (thickness of the O-ring)} \]

O-ring housing channel:

\[ B_4 = 4.1 \text{ mm} \]

\[ h = 2.3 \text{ mm} \]
1.7.3 Flanges (Adapter plates)

In order to mount the force sensor and the embossing head tool at the top of the machine and the voice coil at the bottom of it, two flanges are used (Figure 6.27). These adapter plates in one hand utilize the mounting and demounting of the parts on the slider and in other hand are used to centralize the slider, voice coil and head tool. The material used in this case is stainless steel.

In design of the flange there some elements which should be considered during the design process. First, the mounting procedure of the components on the slider is the main factor. For example, regarding the front flange, first the force sensor should be mounted on the flange and then both components are mounted on the top of the slider. Consequently, the position of the screw holes should be in the ways that provide such a mounting procedure. In addition, the mass of the whole components try to be low while considering the factors like screws diameter, slider central hole diameter, granite drilling limitations.

This figure is omitted due to secrecy agreement

Figure 6.27. Front flange (conceptual model).

In design of the threaded holes and screw sinkings, force sensor and slider screws should be considered which in this case are small head (allen screws) M3 according to DIN standard. Furthermore, a gap between the
head of screws and the surface of flanges should be considered to prevent form double fitting in the model.

The 3D design of the flange between the slider and the voice coil is shown in (Figure 6.28). Here, the mounting procedure of the flange is discussed as follow. At the first step, the flange is screwed to the back side of the slider. At the second step, the actuator of the voice coil is mounted on the flange using M3 screws with allen head. The fitting edge with tolerance of 0.02-0.01 mm on the flange is used to align the flange to voice coil. In the process of design the minimum thickness for flange considered to be 1.5 mm according to DIN standard for allen screw holes and sinkings. All the screws used in this model are Allen hex head screws according to DIN standard. They are the available screws with the smallest head which make the flange as small as possible.

This figure is omitted due to secrecy agreement

*Figure 6.28. Back flange link the voice coil and slider (Solidworkds).*

The centralization of flanges at the top and bottom of the slider is a crucial step in design of slider and flange. In other words, since the flange connects the slider and its components to the voice coil, they should be centralized in order to provide a controllable micro meter motion for the head tool of the machine.

In order to centralize the flanges at both ends of the slider there are two possibilities:

- To use the pin and hole centralization method for the flange and slider.
- To use the sides of the slider and flange in order to centralize them relatively during the assembling procedure of slider parts.
In this design the second method is chosen due to following reasons. First drilling the extra pin holes on the flange needs a bigger part. Second, as it discussed before there is a thickness restriction for the granite slider which requires a bigger flange and slider. Thus in order to reduce the mass and dimensions of the machine the second method is used.

In the second method during the assembly process the flange will be aligned with the slider using the gauge blocks and toloranced side surface of the slider and flange. However, this process needs more time compared to the fist method.

1.7.4 Linear sensor mount

In order to attach the read head of linear sensor to the housing a mount has been designed (Figure 6.29). The housing screws are used to attach the mount to the CFK housing while the sensor screws attach the read head of sensor to the mount. The positions of the sensor screw holes are designed according the screw type of the selected linear sensor. In addition, the head of scanning sensor is faced the sensor scale through the hole at the bottom of the mount. Since the position of sensor read head is adjusted using the seating surface of the mount, this surface should be manufacture with a high tolerance that utilizes required distance of the scanning process. Furthermore, the cable exit place of the sensor should cut out from the mount after manufacturing of this part. The position of housing screw holes should be drilled at the position that the thickness of the housing is more than 1.5 mm. Otherwise; according to the CFK specifications it can cause deformation in the housing.

This figure is omitted due to secrecy agreement

Figure 6.29. Linear sensors mount (Solidworks).
As it discussed in the chapter 1.4.1 (the design of the measurement system of linear motion), the mounting method of the linear sensor offered by supplier company is not applicable in this model. Thus the alternative method which is based on the distance measurement between read head and sensor scale has chosen. As it’s also shown in (Figure 6.30) there is no possibility to reach the sensor form inside the housing in order to achieve the required scanning distance. Thus, according to the second solution, after seating of the linear sensor mount, the distance between bottom surface of mount to the sensor scale will be measured using a linear encoder. Then knowing the thickness of mount at the bottom point, the required distance can be achieved.

The position of the linear sensor mount is crucial in this model. It should be seated in a position that is far enough from the heat sources like voice coil. In addition the bending requirement of the sensor cable should be considered which can influence the performance of the sensor. Furthermore, it should be at the place that the CFK housing has a enough thickness (more than 2 mm).

This figure is omitted due to secrecy agreement

Figure 6.30. The position of the linear sensor mount on the CFK housing (Solidworks).
1.7.5 Air bearing mount

Mounting procedure of the air bearing is a critical step in the assembling process of the embossing head. Furthermore, the position of air bearing inside the housing should be accurate. Thus we need to design a mount in order to attach the air bearing to the CFK housing accurately. In addition, since there is restriction regarding the CFK (housing material) in terms of drilling the holes, it has been tried to mount the air bearing to the housing using glued surface compared to screws. However, the adjustment process of the air bearing mount using glued surface is more difficult compared to screws.

Figure 6.31. Air bearing mount (Solidworks).

Figure 6.31 shows the air bearing mount which has three main parts. First part is the pin holes which are used to adjust the position of the mount inside the CFK housing. Second part is the glued surface which is used to attach the mount inside the CFK housing. The third part is the threaded stud holes which are utilized to mount the air bearing stud in. The outer diameter of the air bearing mount is according the inner diameter of the housing.

In design of the air bearing mount the mounting design of air bearings inside the housing is also considered according to the conceptual model. Although, the design has higher roll stiffness the bearings are not directly across from each other it can be difficult to separate angular adjustments.
from roll adjustments. Furthermore due to shortage of space inside the housing we need to make the bearing studs as close as possible to each other. Thus appropriate shape modifications are carried out in air bearing mount in order to fulfill mentioned requirements.

The mounting procedure of the air bearing is according to the following steps (Figure 6.32). First, the positions of the air bearing mounts adjust inside the CFK housing using accurate linear encoders. It is easier if the positions of the mounts are already cut inside the CFK housing which makes is easier for the assembling technician to adjust the mount at the provided place. Second, the adjusted mounts glue inside the housing. Third, the air bearing studs are drive through the threaded stud holes on the air bearing mounts. Fourth, the air bearings adjust inside the CFK housing using the studs. Fifth, the studs fix on the housing using appropriate nuts and washers. Sixth, the tube path of the air bearings is carried out inside the housing and using suitable T-shape and I-shape Festo connectors. Finally, the air bearings are supplied with air pressure in order to provide the actual situation following with final adjustment of the air bearings. In this step, all the air bearings are linked together in order to provide equal air pressure and air thickness.

This figure is omitted due to secrecy agreement

*Figure 6.32. Air bearing mount in transparent housing (Solidworks).*

In this part the detailed design of the air bearing mount was discussed. In the next chapter the housing adapter plate is provided.
1.7.6 Housing adapter plate

At the front part of the housing, other components like: screw inserts for wire guides, sealing parts and thread inserts are mounted. At the back side of the housing the components such as: the ball bearing, voice coil shaft and ball bearing lock nuts are mounted. Since, there are some limitations for drilling the CFK housing; an adapter plate is designed in order to mount the other parts to the housing.

Figure 6.33 shows the adapter plates in the embossing head which are glued to the CFK housing at the front and back side of the machine. The design of this adapter plates are carried out using the library of Fraunhofer Institute. However, there are some modifications in order to adapt it to this model. The glued surface of the adapter has a sleep of 100 to 1 mm in order to utilize the centralization of the CFK housing and adapter plate.

In design of the adapter plate there are some considerations that should be applied in the modeling process. For example, a 1 mm gap should be considered at the end of the glued surface of the adapter plate. This gap provides a way to extract the glue between the adapter plate and the CFK housing. Furthermore, the positions of the other parts can influence the design of the adapter plate. For example, the air bearing studs are mounted on the CFK housing and the front adapter plate (Figure 6.33). Since drilling the glued surface is not possible two available solutions are discussed as follows. First solution is to increase the length of the CFK housing which cause a bigger embossing machine. Second method is to reduce the length of the adapter plate. The possibility of the second solution is dependent on to the glued surface of the adapter plate in terms of stress strength. Thus, at the next step the strength of the glued surface in terms of applied shear stress will be discussed.
Knowing the specifications of the glue and using the previous adapter plate design from the Fraunhofer Institute library the following calculations are derived. In the first step the shear stress and safety factor of the glued part in previous design are checked.

Measuring the glued area gives:

$$A = 2\pi rh = 14130 \times 10^{-6} \text{ } \text{m}^2$$  \hspace{1cm} (6.16)

Using the area and applied force which in this case are the weight of the front components (achieved using the measurement software linked to the Solidworks) and the embossing force, gives,

$$\tau = \frac{F}{A} = \frac{2.84 \times 10^3}{14130 \times 10^{-6}} = 0.2 \text{Mpa}$$  \hspace{1cm} (6.17)

Knowing the allowance shear stress for the glued part gives:

$$\tau_F = \frac{\tau_c}{S_f}$$  \hspace{1cm} (6.18)
Thus the safety factor which is used in pervious design is:

\[ S_f = \frac{14}{0.2} = 70 \]  

(6.20)

Since the safety factor is high, it makes the model overdesigned. Thus, some modifications are applied in this plate. One possibility is to reduce the glued area that as it discussed before. Thus, the modification of the design is carried out as follows:

By changing the h (length of the adapter plate) form 50 mm to 20 mm the glued area becomes:

\[ A = 2\pi rh = 5652 \times 10^{-6} \, m^2 \]  

(6.21)

Then the shear stress becomes:

\[ \tau = \frac{F}{A} = \frac{2.84 \times 10^3}{5652 \times 10^{-6}} = 0.5 \, Mpa \]  

(6.22)

Checking with stress allowance gives:

\[ \tau_f = \frac{\tau_c}{S_f} = \frac{14}{5} = 2.8 \, Mpa \]  

(6.23)

Comparing allowance stress with shear stress applied to the glued part in the embossing machine gives:

\[ 0.5 \leq 2.8 \]  

(6.24)

Thus, the modification of the design is applicable. The new model of the adapter plate is designed using the new length of the glued part (Figure 6.34). In addition, reducing the length provide the smaller adapter plate at the back side of the CFK housing compared to the previous model.
Furthermore, a new steep (90.57 degree) is considered for the glued part which provides the adapter plate centralization inside the CFK housing.

A threaded area on the adapter is a seat to mount the ball bearing lock nut to secure the ball bearing on the housing. Furthermore, the torque motor shaft is bonded into the adapter plate using the toloranced diameter inside the adapter plate after mounting the adapter to the CFK housing.

1.7.7 Sealing components

The sensors and air bearings are sensitive components which should be sealed inside the embossing machine. Thus, in order to seal these parts against the dirt and dust in the working area of the embossing machine sealing components are designed.

Since the slider, force sensor and the head tool have a 26 mm stroke, the sealing cannot be mounted on these parts. To solve this problem two different models are discussed. The first model is based on the elastic specifications of the flexible sealing using Apple rubber products [17]. In this model the dynamic movement is concentrated in the convoluted area near the inner O-ring in order to apply the 26 mm slider Stroke (Figure 6.35). In this model the outer O-ring will be mounted on the outer housing as a fix part while the inner O-ring is used to seal the force sensor. The Third O-ring utilized a sealed area for linear encoder. Furthermore, the dynamic movement is utilized using the convoluted ring close to the sensor O-ring.
Figure 6.35. Convoluted elastic sealing solution for sealing of the machine (Solidworks).

This second model is based on the air pressure outlet form the air bearings inside the housing. A thin aluminum plate is mounted on the adapter plate of the CFK which provides the sealing effect for the machine. A small gap (1 mm) is designed between this plate and the head tool of machine. Using this gap provides the 26 mm slider stroke possibility inside the fixed housing. In addition, the air pressure coming out form the machine through this gap isolates the components inside the housing. A hole is drilled on this plate for the linear encoder tip with 1 mm gap as before (Figure 6.36).

The specifications of the First model are:

- Lighter sealing design.
- Safer sealing mount.
- More expensive due to specific shape of the model which needs new mould design.
- The O-ring mounting grooves should be designed on the housing which makes the housing bigger.
- Direct contact of the sealing rubber and the force sensor.

The specifications of the Second model are:

- Easy mounting process.
- No need to O-rings due to the air flow through the sealing.
- An adapter plate for the force sensor should be designed to provide the 26 mm slide stroke.
Due to the important specifications like easy mounting process and price, the second model is used to seal the components inside the housing of the embossing machine.

This figure is omitted due to secrecy agreement

Figure 6.36. Sealing components of the embossing machine (Solidworsk).

The spindle bearings need lubrication which is Grease in this case. Consequently, a sealing for the ball bearings is also designed. This sealing protects the machine components against the Grease leakage from the spindle bearing area. This sealing is banked to a shoulder and also glued on the ball bearings rings. However, the rotation of the sealing which is mounted on the CFK housing should be considered in the design process. Thus, a gap of 0.5 mm is considered between the sealing and the upper ball bearing ring (fixed). The same sealing is designed on the lock not of the ball bearings.
7 Design and evaluation of the anti-gravitational system

In this chapter, a solution for supplying the gravitational force to the moving parts of the embossing machine is discussed. As it discussed before the embossing machine is mounted on the test bench vertically. Thus, we face gravitational force which causes some problems in designing of the machine. First, in case the machine is switched off the moving part can fall uncontrollably which can cause damage. Second, the gravitational force can influence the control process of the force in the voice coil.

One solution is to use some edge inside the CFK housing to keep the moving parts inside the housing which are: slider, head tool, adapter plates and relative screws while the other solution is to use a pneumatic cylinder for supplying constant gravitational forces (Airpel).

1.8 Airpel

Airpel is an anti-stiction air cylinder which can supply anti gravitational force. In the Airpel the static stiction is low that provides smooth motion at low pressures, slow speeds and short strokes. The other advantage of Airpel is running without lubrication which is suitable for the areas that need to be clean. In order to achieve ultra low friction, Airpel uses a little air leakage [14]. To eliminate the leakage it requires interference fits between the seal and piston rod, and between the piston and cylinder. At the top of the Airpel a thread area is applied on the piston rod in order to mount the Airpel to the moving components (Figure 7.1).

Since glass is more fragile than steel, Airpel glass part is encased in a stainless steel sleeve with a small space between. The space provides good protection, that the outside wall can be dented without affecting the glass liner. The Airpel can also withstand high stresses and high temperature range without deforming or breaking.
Knowing the specifications of the Airpel and considering the conceptual model this device is applicable in the embossing machine. In order to choose a suitable Airpel in order to provide the anti-gravitational for the embossing head force following parameters are considered:

- Stroke of embossing head: 26 mm.
- Weight of moving parts = 2.5 kg.
- Mounting of Airpel: at this step at the back side.
- Dimensions of Airpel.
- Air supply of Airpel.
- Price.

Considering the parameters above the model M16D37.5N is selected. Since the Airpel is mounted on the back part of the machine, a connector rod is needed to attach the Airpel to the slider. In the selected Airpel due to the threaded surface on the top rod mounting of this connector is applicable. However, the diameter of this adapter should be checked with the diameter of the voice coil central hole.

### 1.8.1 Mounting and alignment system design

The Airpel needs accurate alignment in order to supply anti-stiction stroke. Since, the Airpel is connected to the slider using an adapter rod (Figure 7.3) the alignment of the Airpel should be utilized. Thus, a plate and 8 pair of
spherical washers are used to mount the Airpel properly to the torque motor shaft.

In this alignment set up, the Airpel is screwed inside the Airpel adapter, and then using eight pair of spherical washers, they are screwed inside the torque motor shaft (Figure 7.2). These washers provide the Airpel alignment inside the Torque motor shaft relative to the slider side. In other words, using the spherical washers we can change the angle of Airpel until we find an aligned position of Airpel relative to the slide side.

Thus the mounting procedure of the Airpel is designed as follows. First, the Airpel is droved to threaded hole of the Airpel adapter. Second, the adapter rod is attached on the top of the Airpel. Third, the Airpel system is mounted inside the torque motor shaft. Fourth, the rod screw form the other side of slider is driven into the connecting rod. Fifth, the Airpel is aliened to the other parts and the screws are fastened tightly. Finally the Air pressure supply tubes are attached to the Airpel using an L-shape Festo connector.

In design of the back cover of a gap between the back cover and backside of the Airpel is considered. This 1 mm gap provides the situation for rotation of the Airpel inside the back cover as a fixed part.
In this part the design of the anti-gravitational pneumatic cylinder which utilizes a constant force for the machine were provided. This cylinder is mounted at the back side of the machine which is connected to the moving parts using a connecting rod. This connecting rod is connected to the slider through the central hole of the voice coil. In the next part the experimental evaluation of the Airpel is discussed.

1.9 Experimental evaluation of Airpel

In this chapter, the testing of the pneumatic cylinder (Airpel M9D37.5N) is provided. In this test, the chosen Airpel is examined in terms of the required specifications of the embossing stroke. This test is an attempt to validate the claim of the supplier company regarding the friction less and anti-stiction linear movement of the Airpel (1-2% of the total force).

Considering the different required Characterization of the friction free stock following experiments are performed:

- Measurement with constant air pressure of 4 bar, constant stroke of 8 mm and one waiting period of 2 seconds between the strokes and feed motions (speeds) of 800 and 8000 mm/seconds
• Measurement with constant air pressure of 4 bar, constant feed motion of 3200 mm/seconds, one waiting period of 2 seconds between the strokes and the stroke of 1 mm and 8 mm

• Measurement with constant air pressure (4 bars), constant feed motion (3200 mm/seconds), constant stroke (8 mm) and a maintenance time of 2 seconds between the strokes. The measurements are performed with an off center misalignment of the piston at 10 µm and 300 µm.

During the test, the measurements are utilized for the speeds of 1600 m/sec, 3200 m/sec, 4800 m/sec, 6400 m/sec and 8000 m/sec. However, in this report the results are presented in the figures with only 2 signals, which make it easier to illustrate. In the second test, also, the strokes vary between 1 mm to 30 mm, but the results are presented using only 1 mm and 8 mm.

1.9.1 Performance of the Airpel at different speeds

In this part, the force produced by Airpel is examined in the situation similar to actual model. As is discussed before the Airpel is used to produce constant force during the embossing process. This constant force is the weight of slider and other moving parts, which are attached to it. Thus, In order to provide such a situation for the Airpel a spring is attached to the piston of the Airpel (Figure 7.4). Knowing the stiffness of spring and by measuring the displacement using a linear encoder, the produced force is calculated. The Required instruments for this test set up are:

• Pneumatic cylinder Airpel M9D37.5N:
  o Stroke: 37.5 mm
  o Pressure range: 0,015-7 bar
  o Pressure area in Airpel: 60 mm2
  o Frictional force: 1%-2% of the thrust force

• Air pressure sensor SDET-22T-D6-G14-U-M12 from Festo:
  o Piezoresistive pressure sensor
  o Measuring range: 0-6 bar
  o Accuracy: ± 1% of the measuring range, correspond ± 0.06 bar
- Linear encoder WETA 1/2mm (HBM):
  - Range: 60 cycles per second
  - Measuring range: ± 1 mm
  - Accuracy: 4 µm

- Pressure control valve MS4-LR-1 (Festo):
  - Range of control: 0.25-10 bar
  - Input pressure: 1-14 bar
  - Hysteresis: 0.25 bar

- Spring:
  - Spring Stiffness: 0.46 N/µm

- Boundary conditions:
  - Air pressure: 4 bar
  - Applied force by Air pressure inside the Airpel (Fp) is 24N
  - Stroke: 8 mm
  - Waiting time at the end of each stroke: 2 seconds
  - First feed motion at speed of 800 m/sec
  - Second feed motion at speed of 8000 m/sec

In this test, a linear encoder is fixed to the base, which measures the displacement of the spring. Knowing the stiffness of spring and the measured data by linear encoder the spring force is calculated.

In other side of the Airpel, compressed air is entered to the piston. The applied pressure at the surface of the piston produces a force that will be calculated using the First Newton law at the static condition.

As it is illustrated in Figure 7.4 compressed air, enter the Airpel through the Blue air tube. A pressure control valve is used between the source and Airpel in order to keep the required pressure stable during the stroke. Although, the air pressure considers being constant, due to passive performance of this mechanical valve and also relative hysteresis error, the pressure changes in this test. The clamping sleeve of the linear encoder is
glued to the table. The Cylinder of the Airpel is mounted on the moving edge of the test bench, which provides the required stroke. Furthermore, a linked CNC machine controls the stroke of the Airpel.

The electronic unit that is linked to the test bench collects the data from air pressure sensor and linear encoder which will be loaded in Matlab software later on (Appendix). Then the plotted forces produced by air pressure and the spring will be compared in order to analysis the performance of the Airpel in situations quite similar to the actual embossing system.

This figure is omitted due to secrecy agreement

![Figure 7.4. Test set up for friction measurement in different speeds.](image)

In order to calculate the friction \( (F_R) \) The First Newton’s Law for the Airpel Piston is derived at the static situation (waiting time at end of stroke) as Followed:

\[
\sum F = 0 \tag{7.1}
\]

\[
F_R = F_p + F_F \tag{7.2}
\]
As it is shown in (Figure 7.5) with rising, the speed of the Airpel stroke the pressure peaks, increase and consequently the relative forces become higher. However, at the waiting time of the embossing head the pressure remains constant as it was predicted. In other words, Since the Airpel has a small air leakage the Air pressure at the Airpel remains almost constant during the stroke. In addition, at the waiting time the Air force has a constant value of 0.03 N, which is less than 2% of the static air force of 24 N (0.48N).

The air force in (Figure 7.5) at the positive direction of Z-axis is Larger than the other direction. This is due to the reason that the spring force is added to the Air force in +Z direction while subtracted in –Z direction. It should be consider that the Air force is shifted to zero point in this figure in order to better amplitude measurement.

Figure 7.5. Force produced by Air pressure at different speeds.
Figure 7.6. Spring force at different speeds.

Figure 7.6 shows the spring force in 800 mm/sec and 8000 mm/sec with 8 mm stroke of Airpel piston. With raising the speed of stroke, the amplitude of spring force also, become larger which is more obvious in peak values. In other words, the amplitude of the peaks increases from 1.8 N to 4.6 N with increasing the speed. The reason is by increasing the speed, the acceleration at the start and stop point of the stroke rise, which can affect the applied force. Furthermore, as the speed becomes higher the produced oscillation in the spring at the end of each stroke receives bigger amplitude. Although it was predicted for the spring force at the static time of stroke to be constant, the test shows the amplitude of ± 0.5 N.

Figure 7.7 shows the spring force compared to Air Force in Airpel at 8000 mm/seconds. As illustrated the peak of Air force is occurred at the same time in spring which during the stroke time. In addition, as it discussed before the forces peak value is higher at the positive direction Z-axis.
In order to measure the friction of Airpel, which is claimed to be less than 2% of applied air force, the equation (8.2) is used. Using the mentioned equation shows that the friction amplitude at the peaks has the higher value of ± 2.3 N that is the higher value compared to other time, which is ±, 0.5 N. Thus at the waiting time the friction is around 2% of the static air force of 24 N (0.48N) while, at the peaks this amount is higher. In other words, according to this test the predicted fiction by the supplier company is only applicable in waiting time at the end of each stroke.

![Force vs. Time Graph](image)

*Figure 7.7. Air force and spring force comparison at 8000 mm/sec speed.*

### 1.9.2 Performance of the Airpel at different strokes

In this test, the same test bench is used in order to apply different strokes to the chosen Airpel and analysis the results in terms of friction. The required instruments are the same as chapter 8.1 but the boundary conditions are different. However, the applied stroke in test is varied between 1 and 8 mm while the figures in this chapter show the compared maximum and minimum strokes.
• Boundary conditions:
  
  o Air pressure: 4 bar
  o Applied force by Air pressure inside the Airpel (Fp) is 24N
  o Stroke (ΔZ): 1 mm and 8 mm
  o Waiting time at the end of each stroke: 2 seconds
  o Feed motion at speed of 3200 m/sec

The air force produced by air pressure in the Airpel is compared in 1 mm and 8 mm strokes (Figure 7.8). By increasing, the Stroke the amplitude of the Air force increases with values from $+0.1$ N to $0.3$ N and zero to $-0.1$ N during the stroke time and average amount of $0.025$ at the waiting time of Airpel.

As it discussed in latter test, the amplitude of air force reaches higher value in +Z-direction compared to -Z-direction. The other fact in this test is the higher sensitivity of Airpel in different stokes compared to different speeds in latter test. In other words, the air forces at the different speeds are closer to each other compared to this case with change in strokes.

![Figure 7.8. Air force comparison at different strokes.](image)
Totally, both signals have smaller amplitude than 0.48 N (2 % stat. Air pressure force) which shows the good performance of Airpel concerning the air force.

Figure 7.9 illustrates the spring force at different strokes of 1 mm and 8 mm. During the standing time, the spring force has constant amplitude, while it has peaks during the stroke. The amplitude at the constant waiting time increases from 0.5 N with 1 mm stroke to 1.1 N with 8 mm stroke. The amplitude of spring force at the peaks has a rise from 3.5 N with 1 mm stroke to 3.8 N with 8 mm stroke.

![Spring force comparison at different strokes.](image-url)
The spring force is compared with air force in 8 mm stroke in order to measure the produced friction in Airpel. Knowing the equation (8.2), the different between spring force and air force gives the friction. During the waiting time at end of each stroke the different is 0.5 which is less than the allowed friction limit of 2% (0.48 N). However, this amount is higher at peaks with the average amount of 3.5 N, which is approx. 15% force produce by air pressure in Airpel.

Thus according to this test results, the friction amount claimed by supplier company is not the same in different strokes. In addition is by far more than the friction limit advertized by supplier.

1.9.3 Performance of the Airpel with piston misalignment

In the embossing machine system since there is a distance between Airpel and moving parts the probability of misalignment in piston is considered. Thus, this test is an attempt to measure the Airpel performance considering misalignment in piston. In this experiment, almost the same test bench is
used but the boundary conditions are different. The required instruments are almost the same as chapter 8.2 but the boundary conditions are different.

This figure is omitted due to secrecy agreement

Figure 7.11. Test set up of friction measurement in having misalignment of piston in X-Axis.

In this test instead of the spring, a piezo load cell is used in order to measure the force of bottom side of the piston (Figure 7.11). This sensor is glued to a plate, which provides different position in X-Axis using CNC controller machine, which is linked to the test bench.
- Pneumatic cylinder Airpel M9D37.5N:
  - Stroke: 37.5 mm
  - Pressure range: 0.015-7 bar
  - Pressure area in Airpel: 60 mm²
  - Frictional force 1%-2% of the thrust force

- Piezo load cell 8230C-003:
  - Range: 25 kHz
  - Max. traction power: 2200 N
  - Linearity error in the entire measuring range: < ± 1% load sensitivity: - 4 pC/N

- Boundary conditions:

- Air pressure: 4 bar
  - Applied force by Air pressure inside the Airpel (Fp) is 24N
  - Stroke: 8 mm
  - Waiting time at the end of each stroke: 2 seconds
  - First feed motion at speed of 800 m/sec
  - Second feed motion at speed of 8000 mm/sec

Figure 7.12 illustrates the Air force at changes with 300 µm misalignment in X-direction compared 0 µm. During the standing dc time the air force has constant amount amplitude between stop points, while it has peaks during the strokes. The amplitude at the constant waiting time decreases with average amount of 0.8 N when applying the misalignment and the amplitude of signal at the peaks becomes smaller form 0.35 N to 0.3 N.

In Figure 7.13 the signal achieved from load cell is shown which compared the stroke with misalignment to straight one. The same fall occurs in this figure both in waiting time and during the stroke of Airpel.
Figure 7.12. Air force comparison at different positions in X-Axis.

Figure 7.13. Force measured in load cell comparison at different positions in X-Axis.
In Figure 7.14 the spring force compared to Air Force in Airpel at applying a 300-µm misalignment in X-Axis. The peak in air force is occurred at the same time in spring which is during the stroke. Furthermore, as it discussed before the forces peak value is higher at the positive direction Z-axis.

In order to measure the friction of Airpel which is claimed to be less than 2% of applied air force, the equation (8.2) is used. The friction at the peaks has the higher value of 1.1 N compared to waiting time which has the average of ± 0.1. Thus at the waiting times the friction is less than 2% of the static air force of 24 N (0.48N). However, at the peaks the friction has the higher value than predicted by supplier.

![Figure 7.14. Spring force and air force comparison with misalignment in X-Axis.](image)

In conclusion, the Airpel test can fulfill the required functionality which is constant force during the embossing process. However, the friction in the waiting time of the stroke is less than 2% while this amount increases during the stroke. In addition, the results of the test regarding the misalignment of the Airpel piston are not interpretable that could be due to high sensitivity of the Airpel to the misalignment.
8 Final assembly of the embossing head

In this chapter final modifications and details is added into the embossing machine model. In addition the assembly of the embossing head is provided. In addition the interference between the parts is solved using the interference relief option of the Solidworks software. Furthermore the overall weight of the machine is decrease using length optimization in some parts.

At the end of the machine a hole is considered on the end cover for the cable of the torque motor stator. Since the end cover is fixed to the outer housing and Airpel rotates 360 degrees, it should be a gap between the Airpel end and the Airpel hole on the end cover.

To design the cable path there are some parameters that influence the design. First, the allowance cable bending radius for each component should be respect. Second, the sensor cables should be far from heat sources like voice coil and torque motor. Third, the path of the cables should be secured by suitable clamps. These clamps are screwed to the CFK housing.

Furthermore almost all the cables come out the housing form the top of the machine. Since the housing rotates relative to the outer housing and also the basement, all the cables should guide with a cable holder. This holder will be attached to a cable guide system which provides the movement of the cables.

The other part of the embossing machine which is added in this step is the head tool of the embossing machine. As it discussed before, the optical micro structured shapes are embossed on the substrate using this part. A heating system is also designed for the embossing head tool with frequency of less than 0.1 Hz. the heating system melts the substrate in order to emboss mentioned optical shapes on the substrate. This system is designed by another group in Fraunhofer Institute. However, the results are used at the final design of the embossing machine.

At the top of the embossing machine the head tool is mounted. A heating system is also designed which heat the embossing head tool frequently with (less than 0.1 Hz). The cable path of this system and force sensor also should be gathering into the cable holder.
Figure 8.1. Modified embossing machine (Solidworks).

Figure 8.2 shows the embossing machine without the outer housing, ball bearings rings and top sealing. The CFK housing is shown here as transparent part. At the end of the machine the cooling system is placed. As it discussed in cooling system design a gap should be considered in order to circulate the water flow in the cooling system. The inlet of the cooling system is designed according to the Festo Handbook [16]. Two L-shape Festo connector are used in the cooling system as the inlet of the system.

In order to provide a better stability in the air bearings, they are connected together. On the slider, every two air bearings are connected using I-shape Festo connector. In addition, the air tubes are connected together at the top of the machine in order to provide equal air pressure for each air bearing.

Figure 8.2. Optimization of components inside the CFK housing, the CFK housing is shown as transparent part (Solidworks).

Knowing the all parts mounting requirements, the assembly procedure of the whole embossing system is described as follows:
1. To mount the adapter plates at both sides of slider.
2. To glue the adapter rings at the both sides of CFK housing.
3. To glue the air bearing arc mounts inside the CFK housing.
4. To mount the linear encoder stand on the slider.
5. To mount the voice coil on the slider using adapter plates.
6. To place the air bearings inside the CFK housing and attached the air bearing studs to CFK.
7. To seat the linear sensor head mount on the CFK housing and glue the sensor scale.
8. To calibrate and adjust the read head of linear sensor.
9. To mount the scale of the rotary sensor on the Torque motor shaft and mount the shaft to back side of the voice coil.
10. To seat the spindle bearing at the head of the CFK housing.
11. To seat the spindle bearing distance rings.
12. To mount the other spindle bearing on the CFK housing and secure its position using lock nuts.
13. To seat the outer housing form the head side of the machine in order to bank the head spindle bearing against the shoulder of housing.
14. To bank the stator and cooling system against the shoulder of the outer housing at the bottom side the machine.
15. To mount the Torque motor distance ring.
16. To bank the rotor against the distance ring.
17. To secure the position of the rotor using lock nut.
18. To mount the Airpel using the adjustment system inside the Torque motor shaft.
19. To drive the screw of Airpel connecting rod through the central hole of the slide in order to fix the position of Airpel.
20. To lead the wires at the head of the machine.
21. To mount the sealing part at the head of the embossing machine.
22. To mount the back cover.
9 Conclusion

This work was part of the flexible patterning of micro Structures using embossing technology project as a large scale under the Nan sciences, Nanotechnologies, Materials and new Production Technologies towards sustainability. The aim of the project is the successful development of the adaptive embossing process chain that lead to the economically viable production of optically functionalized surfaces. This technology addresses a demand for advanced light management and illumination sustainable solutions.

In this work, a micro embossing machine was designed in order to manufacture mentioned optically functionalized surfaces. The design process initiated with the conceptual model considering the required specifications of the embossing head. In this step the conceptual design of the three main system of the embossing head which are measurement system, drive system and guidance system were discussed. Then the optimized model was provided in order to use in the next step which is detailed design of the machine.

In the next step the detailed designed of the mentioned main systems of the embossing head were discussed. In addition, the 3D model of the components was designed using Solidworks software. Then two different models were designed and modeled in Solidworks in terms of spindle bearings mounting position in the machine. In the model one; the main goal was to design a light machine with easy mounting procedure. Consequently, in this model the seating positions of the spindle bearings are at the upper side of the CFK housing. This method, utilized enough space for mounting of the air bearings and other components inside the CFK housing. In the second model; the main goal was to achieve more stable machine regarding the rotational movement and vibrations. The position of the spindle bearings optimized in this model to achieve secure holding basements. Thus, the spindle bearings were seated at the both ends of the CFK housing.

The design and experimental evaluation of the anti-gravitational system were discussed in the next step. The Airpel pneumatic cylinder was selected which was combined with alignment system. The performance of the Airpel was examined by three main tests at different speeds, different strokes and considering misalignment. The results of the tests were satisfactory for the
speed range of 800-8000 mm/sec and stroke range of 1-8 mm during the static waiting time of the Airpel stroke. However, the results of the Airpel test considering 300µm misalignment was not interpretable which could be due to the high sensitivity of the Airpel to the piston misalignment.

Finally the assembly of the embossing head was discussed. In additions, complimentary parts and modifications were added to the machine. The cable path of the sensors, voice coil and Torque motor were designed inside the housing.

The designed embossing head tool will be manufactured and assembled in Fraunhofer Institute. In addition the test bench of the whole embossing system will be assembled and tested. The appropriate optimizations will be carried out in order to improve the performance of the machine. Finally the whole set up of the embossing machine will be manufactured in order to produce micro structural shapes on the optical substrates.

These optical substrates are aimed to be applied in different fields such as LED backlighting elements, Lighting and illumination panels and elements. For example, in LED TV the aim is to improve the performance while power reduction of 50%. In street lighting the potential saving would be up to 75% which is 180 000 GWh/year. In conclusion, the design and assembling of the embossing head in this work as part of the flexible patterning of micro Structures using embossing technology aimed to improve the performance of the large scale light applications towards sustainability issues and CO2 emissions.
10 References


5. Y. Desta, Fabrication of high aspect ratio vibrating cylinder micro gyroscope structures by use of the LIGA process, (2005), Department of Mechanical Engineering of the Louisiana State University, USA.


