

Design of positioning system for the plasma needle probe for minimal invasive surgery

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Design of Positioning System for the Plasma Needle Probe

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- ♣ And designing the positioning system for the plasma needle probe

With a lot of experiences and people involved in my live.

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*"Hay hombres que luchan 1 día y son Buenos,
hay otros que luchan 1 año y son Mejores,
hay quienes luchan muchos años y son Muy Buenos,
pero hay quienes luchan toda la vida esos son los Imprecindibles."*
Bertol Brecht

Abstract

The development of a plasma source to be used in medical applications is currently running at the Eindhoven University of Technology. The plasma is a non-aggressive source, which can be applied directly on organic materials and living tissues under controlled conditions. It is truly no-thermal source, operating at ambient pressure and temperature and it does not pose any electrical or chemical hazard for the organism treated. Several feasibility experiments to use the plasma needle in medical applications have been done. At present, the issue is to treat cell samples. Currently, the cell treatment is performed by hand. The scientist places the probe on the top of the cell sample checking by eye the distance between them. Knowing that the doses of plasma depends on the distance from the tip of the needle to the sample, as well as the power supplied and the gas in the ambient, the control of the position of the needle is aimed to get better results during treatment.

As mentioned before, the applied doses of plasma to the sample must be kept constant. For that reason, it is necessary to maintain the distance of the needle tip and the sample constant. Hence, it is important to avoid contact within the plasma and the sample under treatment. These features are going to be the base for this research action. At this work, the design of a positioning system and a control loop for the plasma needle probe are explained.

Several alternatives for each component in the positioning system are given like: different types of the actuators, structures to place the components, and position measurement equipment. After evaluating these alternatives the one that better meets the requirements is selected. The final design is composed of a voice coil actuator used to move and control the position of the plasma needle probe; a leaf spring arrangement to guide the probe in vertical direction; and an inductive sensor to measure the position of the needle tip.

On the basis of this design and the realization of the set up, it can be concluded that the voice coil motor together with the leaf spring arrangement can be used as positioning system for the plasma needle probe.

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Chapter 1

Introduction

The investigation and design of medical instruments has been an aim for the last decades. The development of a plasma source known as the *plasma needle probe* to be used in medical applications is currently running at the Eindhoven University of Technology. Knowing that the plasma working principle is not familiar for people working in the field of engineering and/or medicine, along the introduction some concepts about plasma ignition as well as possible applications are presented.

The project is oriented to the design of a positioning system and a controller for the plasma needle probe. At the end of this chapter the reader will have a clear understanding of the problem to solve and the possible approaches. The positioning of the plasma needle is important since its characteristics depend on the working conditions, the applied gas used for the ignition and the distance between the needle and the sample.

As mentioned before the effectiveness of the treatment with plasma depends on the distance. It is this point, where this work finds its roots, namely a positioning system has to be designed to keep a constant distance between the plasma needle and the cell sample.

1.1 Surface Processing

Several techniques for surface treatment have been studied in the medical field. Nowadays, scientists are interested in discovering new methods and apparatus for this treatment, some applications are presented in this section.

1.1.1 Modification of living tissue

As an alternative to conventional surgery, one of the methods used for the modification of living tissue is *electrosurgery* [14]. This is used to treat damaged surfaces in medical operations. The purpose of electrosurgery is to perform incisions, coagulation and to destroy benign and malignant lesions. Some type of instruments for electrosurgery operate with spark gap generators while another type utilizes electronic circuits consisting of vacuum tubes. This type of device is usually bulky and heavy and they generate an undesirable excessive amount of heat.

A second method for surface treatment is *laser surgery*. It uses a laser light source to remove diseased tissues or to treat bleeding blood vessels. The laser can also be used for cosmetic purposes including removal of wrinkles, tattoos, or birthmarks. This is a well known technique but some drawbacks are incomplete treatment of the problem, infections and scarring.

1.1.2 Cell separation

Various techniques of surface modification have been investigated and successfully implemented at industrial scale. In all these applications, refined treatment is performed using non-thermal gas discharge plasmas.

Using the demonstrated [16] non-destructive character of the plasma, a new application in medicine has been discovered. This application brings the opportunity to treat cell samples [6] using the plasma needle under moderate conditions. Treating the cell sample with the plasma needle, loss of cell contact and cell detachment from the substrate are observed, possibly due to plasma induced damage of cell adhesion molecules. Such a situation is temporary and therefore this technique can be used for cell manipulation (removal and rearrangement without killing cells).

1.1.3 Disinfection of medical instruments

Sterilization or decontamination of surgical equipment has been done using an oven at high temperature for a long period of time. Another technique is to use chemical products to disinfect the instruments. Usage of the plasma for decontamination of surgical instruments is possible, once the plasma is applied to the surface the bacteria are killed by plasma radicals and radiation. This could be used for small or in situ sterilization of medical instruments.

Knowing the background of the different approaches for surface treatment, the inconveniences mentioned above started the research of new instruments which can be used for surface treatment. The plasma needle appears to be a non-thermal and light weight tool for surface processing. It also avoids necrotic tissue and inflammatory adverse reactions. An overview of the plasma source under development is given below.

1.2 The Plasma Source

Plasma [11] consists of a collection of free-moving electrons and ions - atoms that have lost electrons. Energy is needed to strip electrons from atoms to make plasma. The energy can be of various origins: thermal, electrical, light (ultraviolet light or intense visible light from a laser) or, in this case, radio frequency.

The plasma is a non-aggressive source, which can be applied directly on organic materials and living tissues. It is truly non-thermal, operating at ambient pressure and temperature, and it does not pose any electrical or chemical hazard for the treated sample. A non-thermal plasma source [16] generated under atmospheric pressure using radio frequency excitation is intended to be used to perform fine cell manipulation and high precision plasma surgery, like the removal of (cancer) cells or cleaning dental cavities.

The plasma is created in a shielded cast that contains a needle of 5 cm long, with a diameter of 1 mm stainless steel wire with sharpened tip, see figure 1.1. The wire serves as the powered electrode, and it is placed coaxially within a grounded metal cylinder with 1 cm inner diameter (see figure 1.1). The glow produced by the plasma in the tip of the needle is of an intermediate size (0.1-1 mm).

Some advantages of this plasma needle method for surface processing are:

- ✓ Low-power, low-voltage plasma source
- ✓ Non-destructive character
- ✓ Low temperature plasma (no-thermal damage)
- ✓ Operation at room temperature and atmospheric pressure

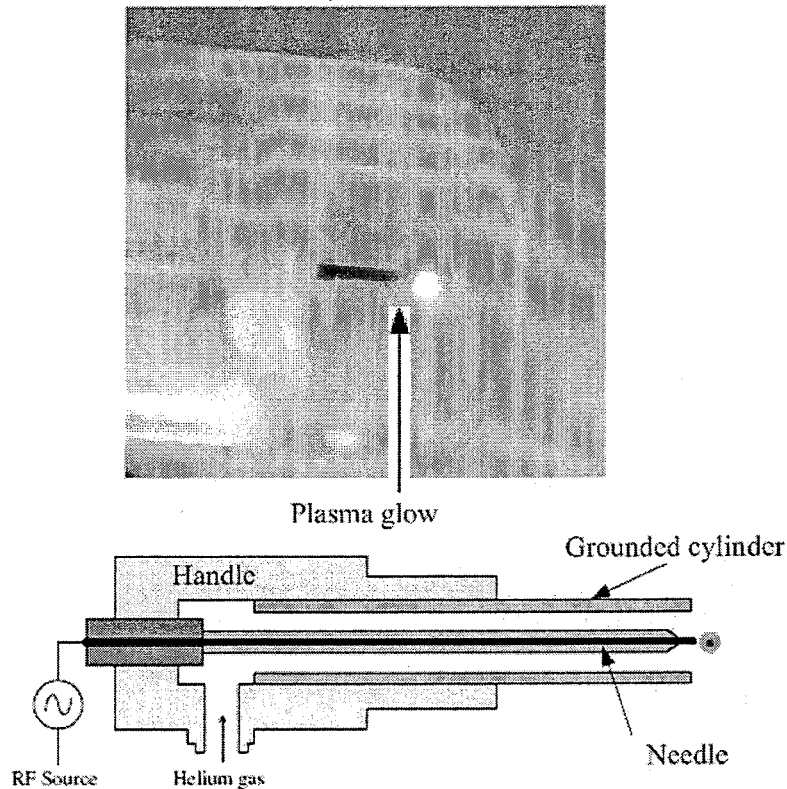


Figure 1.1: The plasma needle

✓ Biocompatible

To conclude, the plasma is the creation of an electrical field at the end of the tip of a metal needle. It is used to treat surfaces as has been showed in this introductory chapter. Hereafter, a future application is discussed which is currently under development.

1.2.1 Movable tip

A future application of the plasma needle consists of a catheter to maneuver through the vascular system to locally treat diseases. To that end, an articulated tip would be used to position the needle in the diseased area, some ideas are given here that could be used in future research.

The idea is to achieve bistable positioning of the needle tip. With this purpose a cylindrical embodiment is created using a composite of two materials: Shape Memory Alloys (*SMA*) and Shape Memory Polymers (*SMP*) [17]. This composite structure is created by molding the polymer around the deformed alloy SMA as shown in the figure 1.2 and cited in the patent.

These materials have unbiased operating temperatures, that allows to control the stiffness of the structure by varying the temperature. Therefore, by controlling the heating temperature of the composite, the actuation is regulated. The composite is heated in order to deform it and when it is cooled down the position is frozen.

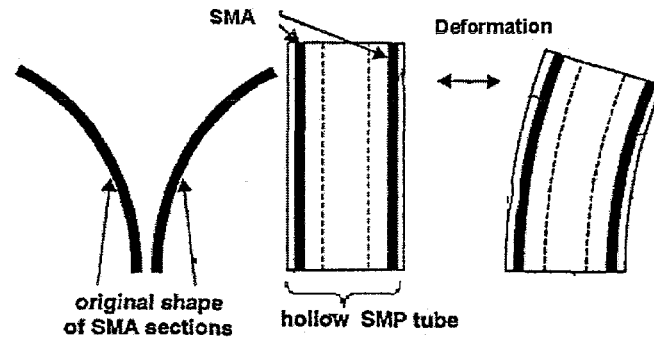


Figure 1.2: Shape Memory Alloy and Shape Memory Polymer composite

The creation of a bistable actuator, as is proposed in the patent [17] is accomplished by placing the glass transition temperature of the SMP within the hysteresis loop of the SMA's transformation. The intersection between the lines is the working transformation temperature of the composite.

This contribution is the starting point for the development of a future application of the plasma needle in medicine.

1.3 Problem definition

Several feasibility experiments to use the plasma needle in medical applications have been done. Here, the issue is to treat the cell sample with the plasma needle, where the distance between the tip of the needle and the cell sample is constant during the treatment. The duration of the treatment is in the range of 10 to 30 s, depending on the type of medium in which the cells are placed and the required treatment.

At present, the cell treatment is performed by hand. The scientist places the probe on the top of the cell sample, checking by eye if the distance to the sample is around 2 mm, then he fixes the probe and the treatment starts. Once the treatment begins the sample is moved horizontally by a manipulating stage.

Knowing that effectiveness of the surface treatment using the plasma needle depends on the power supplied, the timing, the gas composition and the doses of plasma, which is related to the distance between the tip of the needle to the sample. An improvement in the positioning of the plasma needle is intended to achieve better results.

Therefore, the aim of this research is achieving a controlled surface treatment with high precision. This is accomplished by the design of a positioning system that accurately places the needle probe above the cell sample. The system includes means to measure and control the distance between the needle and the cell sample.

1.4 Project survey

Starting from the objective mentioned above, the design of the positioning system is divided in two parts:

- The first part enclosed in Chapter 2, which presents some alternatives for the positioning system. It includes different types of actuators to move the probe along the z-axis, the configuration of the structure to place all the components and the sensor to measure the distance. These alternatives have been studied and finally one is chosen that fulfils the requirements in table 2.1.
- The second part is the development of a plasma needle probe with the capability to place it accurately above the specimen (z-movement). A detailed design of the components and selected hardware is presented in Chapter 3, this is used to purchase or built the components for the construction of the set up. Afterwards, a model of the system is obtained and simulated in Chapter 4, this allows to conclude with the comparison of the simulations and the measurements in the set up.

Chapter 2

Designing Alternatives for the Positioning System

The design of the positioning system is divided in three parts: the selection of the actuator, the calculation of the structure to place the components, and the selection of an appropriate control system to position the plasma needle.

A clearly definition of the requirements of the application is obtained after a discussion with the final user, in this case the scientist that works with the treatment of cells. The outcome of this discussion is the list of requirements that are recorded in table 2.1. To accomplish these demands several alternatives are proposed, which are summarized in this chapter.

| | |
|------------------|--|
| High accuracy | The system should be able to place the needle in the vertical position with a precision of 0.1 mm. |
| Stiffness | Offering the maximum immovability to locate the needle tip in the desired position. |
| Low interference | The power consumption of the positioning system has to be very small. |
| Mass | Probe plus actuators 600 g. |
| Stroke | The movement: vertical distance of 10 mm. |

Table 2.1: List of requirements

At first, the possible actuators that can be used are shown together with their characteristics. Later, options for the structure and guiding mechanism are discussed.

2.1 Selection of the actuator

The actuator is a device that can influence the controlled variable of the process. In this case, the controlled variable is the distance between the needle tip and the cell sample. The actuator must allow controllability in both forward and backward direction. It is important to consider the influence it has in the overall system, e.g the necessary power consumption or the vibrations it causes when moving.

Some of the actuators move by the rotation of an axis, the translation of a spindle, or the expansion of thermoreceptor material. An actuator can affect the performance of the driven system. Moreover, what is the influence of the actuator in the overall systems response? Considering this, some options

for the actuator and its characteristics are listed next:

- **Piezoelectric:** A piezo-actuator converts electrical energy to motion and or force that is coupled to an external mechanism. Stacks are capacitors that change shape when charged with high voltage.
Drawbacks: High voltage, short stroke.
Advantages: Nanometer resolution movement, no magnetic fields or vacuum operation.
- **Linear Stepper Motor:** A linear stepper motor divides linear distances into discrete incremental moves called steps. The size of each step is determined by the spacing of the steel teeth in the platen and by the way the coils are energized.
Drawbacks: High static friction in the system, non-sinusoidal character of the torque versus shaft-angle curves and digital control systems is necessary.
Advantages: High Torque at low speed, high repeatability [5]
- **DC Motors:** The force exerted on a current-carrying conductor that is in a magnetic field causes the conductor to rotate. This rotational force is the torque used to move a load. There are different types of DC motors like: permanent magnet, shunt wound, series wound motors, compound and brushless motors .
Drawbacks: Requires more current than permanent magnet motors, since field coil must be energized. Generally heavier and bigger than others. Rotational movement instead translation.
Advantages: Wide range of speeds and torques. The control is based on the regulation of the input current.
- **Voice Coil Actuator:** A Voice Coil Actuator is made up of two components, a moving member and a fixed member. The core of the moving member is basically a group of coiled wires in a tubular form. The stationary member is made up of a permanent magnet that surrounds the outer layer of the coil and a ferromagnetic magnet of the inner structure that completes the magnetic field radiating through the coil of the moving member. By applying a voltage across the leads of the coil, the magnetic field produces a force on the moving member, creating linear motion.
Drawbacks: It has to work in a feedback control loop.
Advantages: the force is proportional to the applied current.

Comparing the characteristics of the actuators mentioned before, it is observed that the voice coil has some valuable features like:

- It is a direct drive linear actuator. The linear movement is transmitted directly to the load, avoiding the use of extra connections.
- The actuation force can reverse direction by just switching the direction of the current. It allows a simpler control by changing the sign of the supplied current.
- There is only one moving component, in this case the coil. The moving mass is small, therefore the influence of the moving mass of the actuator with respect to the overall response of the system is less influencing. There is less dynamics involved in the system.

In the next chapter more information about the selected voice coil actuator is given, such as specifications of the load capacity and voltage supply.

The actuator must be connected to the load, the plasma needle probe, to obtain a controlled vertical movement. This means that the structure supporting the components as well as the guiding mechanism, plays an important role. This structure must retain the components in a fixed position, preventing them to move in an undesired direction. In the next section this is going to be explained in more detail.

2.2 Alternatives for the support structure

Any body has a number of independent movements that are called the Degrees of Freedom or DOF see figure 2.1. Depending on the application, some of these DOF must be fixed .

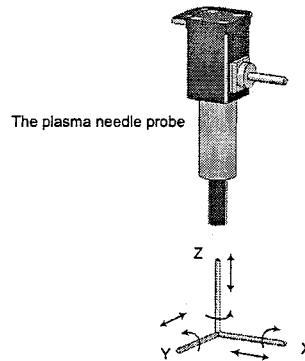


Figure 2.1: Free body diagram (DOF)

In case of the plasma needle probe, the body needs to move in the vertical direction, along the z-axis. Therefore, the remaining 5 DOF, i.e. rotations in x, y and z as well as the translation in x and y must be fixed. A method of accomplishing the fixation of the undesired DOF is to use flexures or elastic elements. These can be blades, ropes, or beams, which have the property to be stiffer in some directions than in others. Therefore, depending on its connection to the body it is immobilize or not, this is explain in more detail in the next section.

- Ball bearings guiding system

This one leads the plasma needle probe using a 3 contact point guiding system. The three coplanar contact points would fix 5 undesired DOF, see figure 2.2.b. To obtain this, three balls are shifted 120° and placed coplanarly as shown in figure 2.2.a, thus the forces created between the contact surfaces are compensating the translation and rotation of the body. It allows a linear translation of the body along the vertical axis as shown in figure 2.2.c.

The balls must be pre-stressed which complicates the construction of the guiding system. This kind of construction is used where high accuracy is required. In this case the accuracy is 0.1 mm, which is not consider to be very high. Therefore, other alternatives could offer the same functionality with a simpler structure.

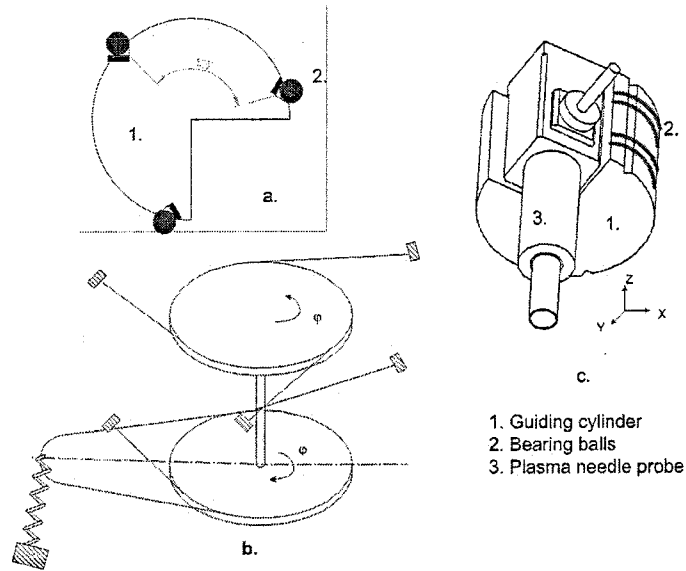


Figure 2.2: Bearing balls guiding system

- Linear bearings

These are linear guiding systems, which consist of an outer sleeve with raceways having axial bores and a retainer with several ball guideways. These ball guideways, see figure 2.3.a, are distributed over the periphery of the retainer and comprise axial guideways with semicircular deflecting ways connecting these guideways by pairs, and endless ball races located in these ball guideways see figure 2.3.b.

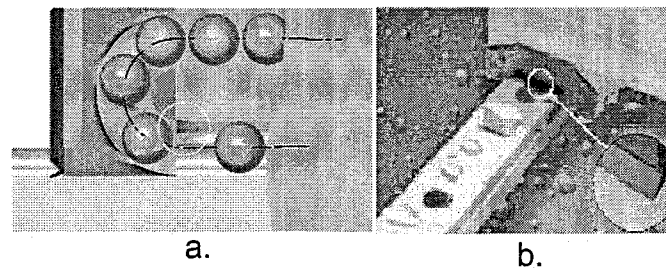


Figure 2.3: Mini rails guiding system

The compact design of the miniature profile rail guides permits maximum performance on a minimum of mounting space. The rails are grounded on all faces and its length is according to the requirements. Carriages are available for different pre-loading cases and the choice between sealed and open types allow the systems design to adjust to the requirements.

The determination of an appropriate pre-load renders the miniature profile rail guide suitable for widely varying operating conditions. Some of the selection parameters are: the load carrying capacity, which is the static load rating that corresponds to an arithmetical Hertzian pressure¹ of 4,200 MPa between raceway and balls, the life calculation, and the permissible maximum load. There is more information available in [12].

The configuration using the mini rails as a guiding system proposed for this specific application is drawn in figure 2.4.

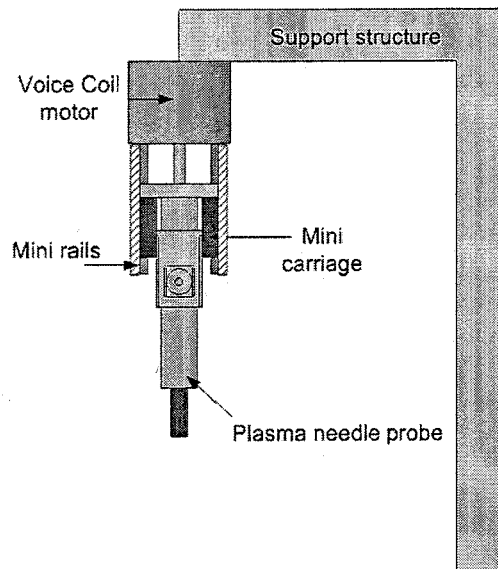


Figure 2.4: Mini rails guiding system

The rails must be aligned in front of each other, to obtain a straight trajectory of the translating body placed in the middle. To fulfill the alignment requirements, an accurate placement of the rails in the structure is a critical point of this alternative. These rails are ideally designed to perform operation in the horizontal plane, while the present application requires guiding in the vertical plane, therefore this alternative is dismissed.

- Leaf spring arrangement

The basis for kinematic design is constraining the right number of DOF. Maxwell [9] describes: "If a solid piece is constrained in more than six ways it will be subjected to internal stress, and will become strained or distorted" which is undesirable. The right kinematic design is obtained constraining the exact number of DOF, e.g. translations and/or rotations. This statement is the starting point for the alternative presented hereafter.

To constrain one translational DOF, the classical solution is the use of a slender rod, like in figure 2.5. Some examples of fixing one translational DOF are given here, as well as in [7]:

Figure 2.6 shows some examples for constraining 2 DOF, which can be achieved by two rods like in figure 2.6.a or a hinged leaf spring, like in figure 2.6.c.

¹The Hertzian pressure must not exceed the tensile strength of the mating steel profile in order to avoid depressions in the profile

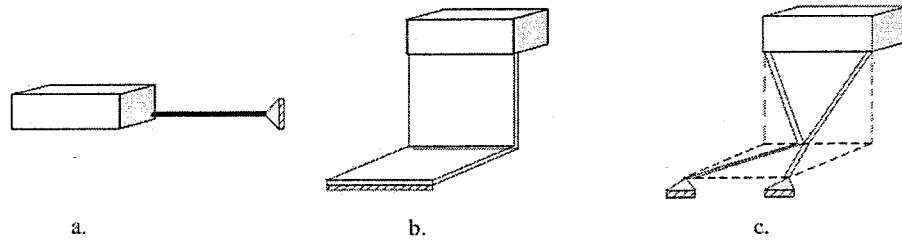


Figure 2.5: Single DOF constrains for translation

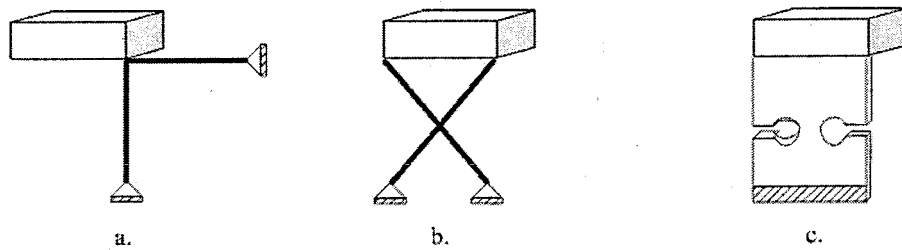


Figure 2.6: Two DOF constrains for translation

By combining the elements mentioned before more degrees of freedom can be constrained, like the three DOF constrained in figure 2.7 by 3 rods (figure 2.7.a) or by normal leaf spring (figure 2.7.b).

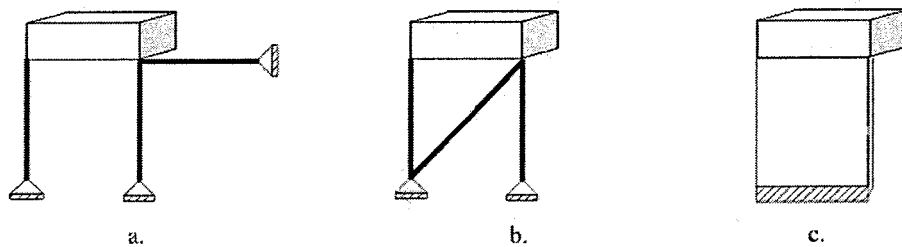


Figure 2.7: Two DOF constrains for translation, one for rotation

The leaf springs are elastic elements that have the property to deform in a desired direction while the others have a relative high stiffness. Therefore, by using leaf springs made of flexible but stiff material, the body to be fixed is fastened in the desired DOF. In the case of the plasma needle probe, the $(x-y)$ translation as well as in the rotations around (x,y,z) must be fixed. This is done using the configuration shown in figure 2.8, which is the selected alternative. In the next chapter the detailed design is carried out, it includes the material selection, design calculations and the drawings for the construction.

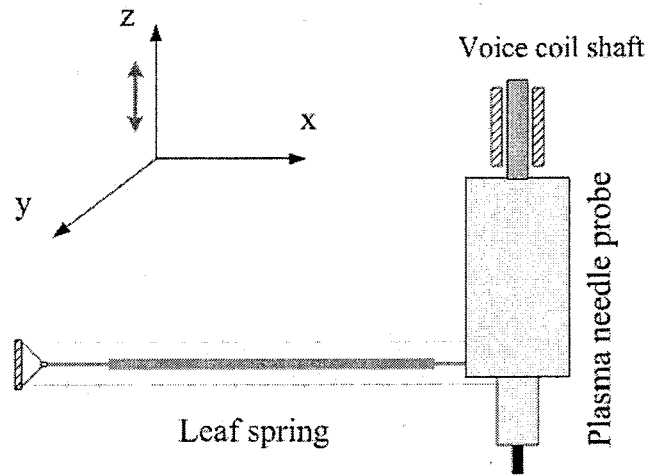


Figure 2.8: Five degrees of freedom constrained

To understand the criteria for the material selection, it is necessary to recall some concepts from material science like:

- *Yield point*, which is usually defined in terms of the stress that causes 0,2 percentage of plastic deformation.
- *Ultimate tensile stress*, is the maximum value of strain where the part starts necking and stress begins to increase with increasing strain until fracture occurs.
- *Modulus of elasticity*, is the material type's effect on the spring constant of the system, which can be used to calculate the bending stress on the material.

These are the three main characteristics that have to be taken into account once the material is selected for the construction of the leaf springs.

Chapter 3

Detailed Design

The previous chapter formulates several alternatives for the selection of the actuator and structure to use in the positioning system. This chapter covers the design calculations for each one of these components, and its combination resulting in the first prototype for the positioning system of the plasma needle probe as shown in figure 3.1. Therefore, design calculations for the support structure using the leaf spring arrangement, the voice coil actuator and the control loop are encountered as follows.

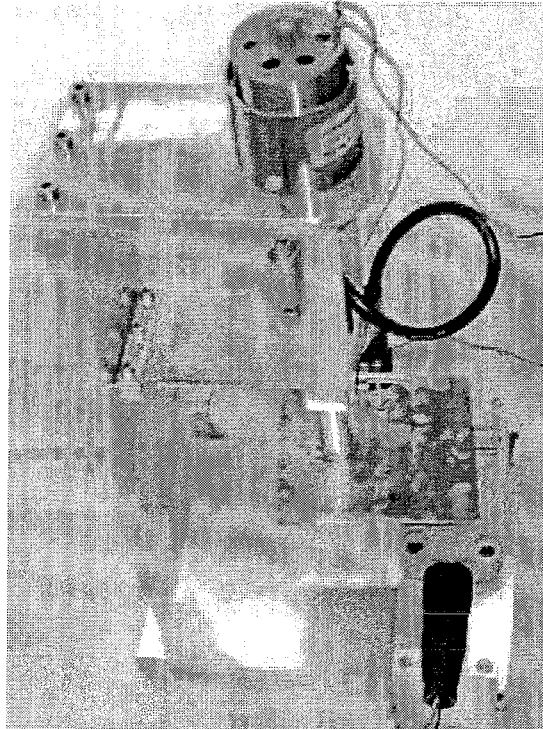


Figure 3.1: Positioning System Designed

3.1 The support structure

The goal for the support structure is to fix five undesired degrees of freedom of the plasma needle probe. Constraining these five undesired DOF is obtained using the leaf spring guiding system as shown in figure 3.1, which is going to be explained in the next section.

3.1.1 Material selection

The leaf springs is bending, is flexible and it must be built in a non-magnetic material, in that the voice coil motor cannot be surrounded by magnetic materials, to prevent disturbing the electromagnetic field. Considering these features the material selection is as follows, there is a detailed explanation of the calculations and at the end of the section in table 3.1 the results are given.

A method to compare different materials is to calculate the *bending stress* [7] and determine the length of the leaf spring necessary to achieve the required z displacement. Hence, using the maximum yield strength of the material as bending stress σ and giving approximate values for thickness and width of the leaf spring see figure 3.2, the maximum length l is calculated.

$$\sigma = \frac{3Etz}{l^2} \quad (3.1)$$

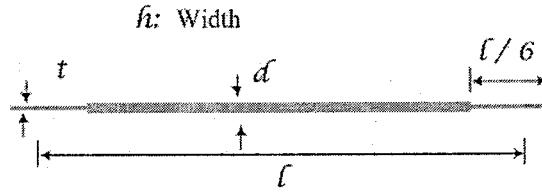


Figure 3.2: Leaf spring dimensions

As a result of this calculation, the material that allows the required 10 mm deformation is the AISI 316 and is also non-magnetic, see appendix A. Therefore, this is the selected material for the construction of the leaf spring.

The calculation of the *transverse stiffness*, is obtained using equation (3.2) but now using the calculated length l , see figure 3.2 for the dimensions present in the formula, the ratio between the length l and the width h must be about one to ensure the fixation of the DOF. The transverse stiffness will influence the movement of the motor, represented as an opposing force which is calculated with equation (3.3), this value is taken into account for the calculation of the peak force of the motor that will be presented later on in the detailed design of the voice coil actuator.

$$C_{zz} = \frac{Eht^3}{l^3} \quad (3.2)$$

$$dF = C_{zz} * z \quad (3.3)$$

Another calculation is the *alongside stiffness*, which represents how stiff the leaf spring is to side disturbances. It is calculated with equation (3.4):

$$C_{xx} = \frac{3Eth}{l} \quad (3.4)$$

The leaf spring has a flange with a thin strip attached to it (which acts as stiffener) which is screwed to the structure and to the plasma needle probe. A force is created in this connection, acting on the two ends of the leaf spring. If the force is not too large, the deformation of the flange will be very small, but once a certain threshold is crossed, the flange will *buckle*. Such buckling is a form of engineering failure, and therefore it is interesting to find the minimum force or loading under which will occur, this is known as *buckling force* F_K .

$$F_K = \frac{36 \pi^2 E I}{l^2} \quad (3.5)$$

The deformation of the leaf spring structure is not completely straight see figure 3.3. There exist torsion which is calculated by equation (3.6):

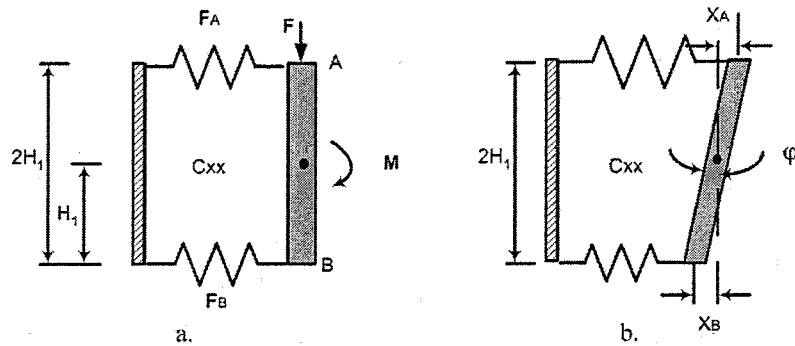


Figure 3.3: Torsion

$$\varphi = \frac{X_B + X_A}{2 * H_1} \quad K = 2 * H_1^2 * C_{xx} \quad (3.6)$$

A complete derivation of equation (3.6) is available in Appendix A. Assuming that the plasma glow has a minimum diameter of 0.1 mm, it represents the limit of deviation on the horizontal plane for the positioning of the needle tip to perform a good treatment. Therefore, the maximum allowed displacement for the application X_B equals to 0.1 mm,

To calculate the maximum rotation φ , first the moment (M) produced by the mass of the box that connects the plasma needle with the leaf springs and the motor is computed using the equation (3.7) torsional stiffness K .

$$\varphi = \frac{K}{M} \quad (3.7)$$

The results of the calculations for the leaf springs are given in the next table 3.1 and the drawings are shown in Appendix D. To continue the design the support structure to place all the components like the voice coil motor, the leaf springs and the plasma probe is given now.

| | | |
|-------------------------------|-------|----------------------|
| Leaf spring length | [m] | 0.05 |
| Transverse stiffness C_{zz} | [N/m] | 11.91 |
| Force opposing the motor | [N] | 0.1 |
| Alongside stiffness C_{xx} | [N/m] | $2.90 \cdot 10^6$ |
| Buckling force F_K | [N] | $1.93 \cdot 10^8$ |
| Torsional stiffness K | [N/m] | $9.50 \cdot 10^3$ |
| Maximum deviation φ | [m] | $9.75 \cdot 10^{-6}$ |

Table 3.1: Leaf spring calculation results

The voice coil motor is connected to the plasma needle probe using an interface box see figure 3.4, which is designed to house the coaxial cable connecting the plasma probe to the power supply as well as the connection for the leaf springs and the voice coil motor, the detailed drawings are in Appendix D. The material selected to construct the box as well as the structure to place the components is aluminium, because it is a light material, easy to manufacture and non-magnetic. Some calculations to prove this are given now:

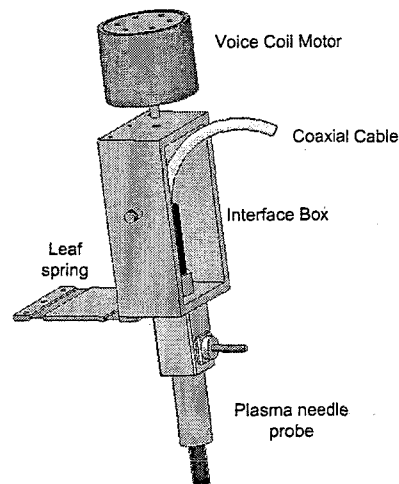


Figure 3.4: Torsion

Looking at the figure 3.5.a the voice coil is placed on the top of the structure and aligned with the plasma needle probe. Assuming that the load is concentrated in one point see figure 3.5.b of a cantilever beam, calculate the deflection caused by the load.

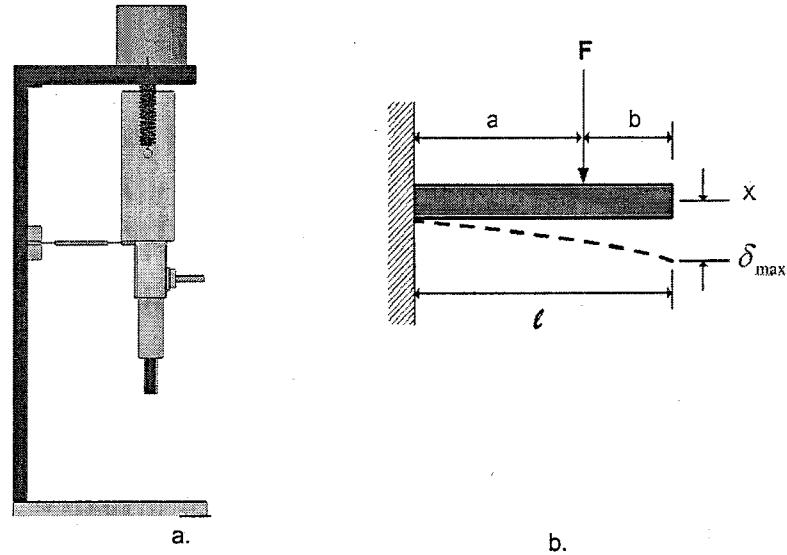


Figure 3.5: Support structure

The force F is the resultant of the summation of all the aligned masses and it is used to calculate the deflection on the beam with equation (3.8). The maximum allowed deflection is 0.1 mm, which is considered to be the maximum position error in vertical direction, the value of maximum deflection is $4.44 \cdot 10^{-2}$ mm using aluminium. The calculations are given in Appendix A and the drawings in Appendix C.

$$\delta_{max} = \frac{F a^2}{6 E I} (3 l - a) \quad (3.8)$$

The motion system is the next step in the the positioning system. This is performed by a voice coil motor placed upside down as shown in figure 3.5. When there is no current flowing through its coils, the moving member (the coil) will fall. The probe is connected to the shaft of the motor and it is connected to the moving member. Then, the probe will fall if there is no applied current in the coils, causing the needle tip to enter in contact with the cell sample, which is undesired. To counteract this action, two compensating springs are selected. These springs are placed each one at a side of the box, and stretched until the structure. These springs has been selected such like they are stiff enough to compensate for the mass of the probe, while they are not to strong, to avoid requiring extra force of the motor. The spring constant is 0.25 N/mm and the extension length 86.10 mm.

3.2 The voice coil actuator

Four parameters determine the selection of the voice coil actuator:

- Peak force (F_p): This is the force acting directly at the actuator at all times. In this case it consist of, the weight of the probe summed to the opposing force, due to the leaf springs and the resisting force of the spring used for mass compensation. The values are in table 3.1. Other factors may contribute to the overall force requirement. Their values are difficult to determine, therefore they are taken into account by using a safety margin of 20% of the calculated force value.

| | | |
|---------------|------|-------|
| Probe | [Kg] | 0.09 |
| Support probe | [Kg] | 0.116 |
| Springs | [Kg] | 0.03 |
| Voice coil | [Kg] | 0.255 |
| Total Mass | [Kg] | 0.66 |
| F_p | [N] | 7.75 |

Table 3.2: Peak Force

- RMS force requirement (F_{RMS}). The Root-Mean-Square or RMS force is used to approximate the average continuous force of an application. It is calculated as follows:

$$F_{RMS} = \sqrt{\frac{F_P^2 t_1 + (F_L + F_F)^2 t_2 + (F_m - F_L - F_F)^2 t_3}{t_1 + t_2 + t_3 + t_4}} \quad (3.9)$$

Where:

| | | | |
|-------|----------------------------|-------|--------------------------|
| F_P | Peak force | F_L | Load force |
| F_F | Friction force | F_m | Acceleration of the mass |
| t_1 | Acceleration time, seconds | t_2 | Run time, seconds |
| t_3 | Deceleration time, seconds | t_4 | Dwell time, seconds |

The RMS force for this application is 0.35 N.

- Linear velocity (ν). This is dictated by the type of movement, it could be a point to point movement, or a constant force application. In this case the load has to be positioned point to point.
The actuator must have a rated velocity larger than the average move velocity. The velocity is calculated assuming that the load has to move along a stroke of 10 mm during an approximate time of 5 seconds. The velocity is then: 0.002 m/s.
At the same time the actuator generates a back electromotive force (*emf*), that is proportional to the speed of the moving coil, it is calculated with equation (3.10):

$$V_B = \nu K_b \quad (3.10)$$

The back *emf* resultant for the application is 0.0224 V.

- Total stroke or move distance (D). As mentioned above the moving distance is 10 mm.

The environmental requirements will also affect the actuator selection. However, in this specific case the conditions are not severe. The equipment will be used in a clean environment at ambient temperature. For that reason, there are no restrictions in the construction of the actuator.

Finally the voice coil actuator selected has the characteristics given in table 3.2:

For the position control mode, additional feedback elements are added to the system as mentioned by the manufacturer in this reference [2]. A position sensor is needed to measure the position and use it to control the input voltage of the voice coil, it is going to be explained later on.

| | | |
|---------------------------------------|---------|--------|
| Voice coil actuator | | VM4032 |
| Number of turns | [t] | 362 |
| Velocity constant | [V s/m] | 11.2 |
| Force constant | [N/A] | 0.029 |
| Thermal resistance | [C°/W] | 8.40 |
| Coil resistance | [Ohm] | 12.8 |
| Mass of the voice coil, moving member | [Kg] | 0.025 |
| Stroke | [mm] | 9 |

Table 3.3: Actuator selected

3.3 The position sensor

The position control system is composed of an actuator, the plasma needle probe and a sensor. The sensor measures changes in the distance in z-direction and generates an electric signal proportional to it. This measurement is compared with a reference position and gives the error that is compensated by the controller. This generates a control signal that affects the voice coil motor changing the distance and minimizing the error. To select the sensor some requirements are given:

- ✓ The sensor must be able to track distance changes of 0.1 mm
- ✓ Measure the distance in a non-contact way

Some ideas for measuring the distance are given in the work of van der Laan [18]. In his work, is demonstrated that the measurement in the variations of the reflected power of the plasma, is related to distance variations. It is an effective non-contact technique to measure the distance, which could be used in the positioning system of the plasma needle.

Hence, in this design the sensor used to measure the distance is an inductive type. Inductive sensor generates an electromagnetic field that is reflected by a metallic object that is a moving part of the machine. The sensor has a proportional output voltage to the distance between the active surface of the sensor and the reflective surface. This type of sensors are accurate, durable, and it has a quick response time. The sensor is non-contact and covers the accuracy required by the application, detailed information is given in Chapter 4.

Chapter 4

Modeling and experimental results

In this chapter the derivation of a mathematical model describing the behavior of the positioning system is given. Next, the unknown parameters, such as stiffness of the system, present in the model are calculated and later on some simulations and measurements will be used to validate the estimated values and the model of the system. With these results, the design of the positioning systems is completed as described in the problem definition section 1.3.

4.1 Modeling

In this project the overall goal of positioning control is to cause the output position to keep a constant distance between the needle tip and the cell sample with the use of feedback. This goal is met as the result of several simple steps. The first one, was to select the best alternative for each part of the positioning system by choosing the actuator, the structure to place the components and the sensor to measure the distance.

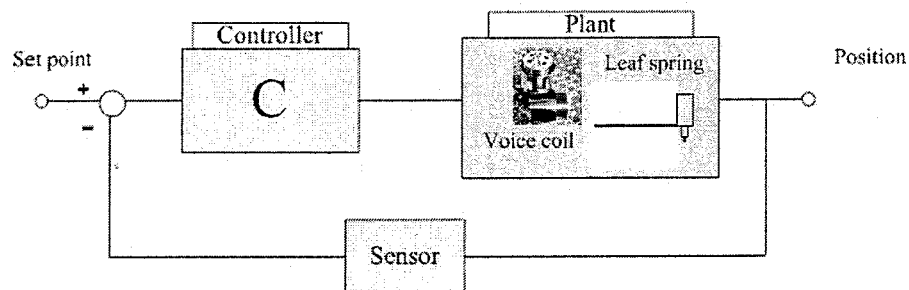


Figure 4.1: Control diagram

Secondly is the development of a mathematical description of the process to be controlled figure 4.1 to finally come to the design of the controller validated by comparing measurements and simulations. The dynamical model is a set of differential equations describing the dynamic behavior of the system. Using the equations of motion in terms of a state space description.

The system to be controlled consist of:

- The actuator: a voice coil motor
- The load: the plasma needle probe together with the guiding system
- Feedback element: the position sensor

The model of the system is obtained using the second law of Newton together with Kirchhoff's laws. The voice coil motor is described by

$$\begin{aligned} V &= V_R + V_L + V_e \\ V &= I * R + L * \frac{dI}{dt} + Bl * \frac{dz}{dt}, \end{aligned} \quad (4.1)$$

where R is the voice coil resistance, L the inductance and Bl the velocity constant.

The mechanical part is described by the equation of motion

$$M\ddot{z} + b\dot{z} + K_s z = F, \quad (4.2)$$

with M the total mass of the system, b the viscous friction coefficient and K_s the spring constant.

Hence, the connection of the electro-mechanical system is

$$F = K_e * I, \quad (4.3)$$

where K_e is the electrical voice coil constant.

The total electromechanical system in state space description is obtained as follows. The state vector is defined by

$$x = [z \dot{z} I]^T$$

leading to:

$$\dot{x} = \begin{pmatrix} 0 & 1 & 0 \\ -K_s/M & -b/M & K_e/M \\ 0 & -Bl/L & -R/L \end{pmatrix} x + \begin{pmatrix} 0 \\ 0 \\ 1/L \end{pmatrix} V \quad (4.4)$$

$$y = [1 \ 0 \ 0] x$$

To validate this model, it has to be compared with the frequency response measurements performed on the real set up. To obtain the measurements, the first step is to calibrate the position sensor.

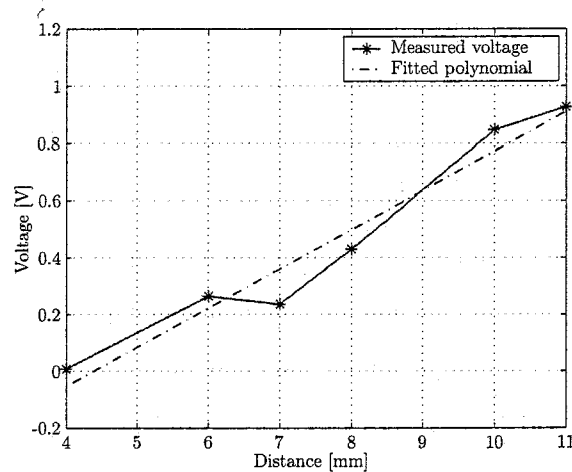
◊ Sensor calibration:

The inductive sensor provides a linear output signal relative to the distance between the target and the sensor's active face over the entire measuring range.

The measuring range used for this application is 4 to 11 mm. To utilize the full measuring range, it is important to work with an appropriately sized target, which may also be a moving part of the machine.

Thus, the target surface is a plate glued at the needle tip.

The sensor is calibrated using the voltage measured with a voltmeter at a fixed distance. The distance is fixed using measuring blocks, these are placed between the plate and the sensor's active face. The motor is moving until the plate touches the block and at this point the block is taken away while the output voltage is read. The measurements are displayed in table 4.1. The best fitting curve to the obtained set of points is found by using least squares estimation, the estimated polynomial is $z \text{ [mm]} = \frac{V+0.6034}{0.1376}$.



| | | | | | | | |
|-----------------|------|--------|--------|--------|--------|--------|--------|
| Measuring block | [mm] | 4 | 6 | 7 | 8 | 10 | 11 |
| Voltage | [V] | 0.0070 | 0.2640 | 0.2350 | 0.4300 | 0.8470 | 0.9270 |

Table 4.1: Sensor calibration

After the sensor is calibrated the frequency response measurements are obtained as presented in the next section.

4.1.1 Frequency response measurements

The electromechanical system consisting of the voice coil motor, the guiding system and the plasma needle probe is going to be referred as *plant*. Frequency response measurements require the excitation of the plant at all relevant frequencies. Therefore, the plant is excited with a signal that is sufficiently exciting but not harmful for the components present in the plant. Some restrictions are taken into account, like:

- The voice coil motor has a maximum input voltage of 10 V.
- The leaf spring arrangement used for the guiding has a maximum buckling force of $1.93 \cdot 10^8 N$.
- The plasma needle must be out of service while measuring at high frequency excitation.

The input signal used is the summation of a random number with zero mean and variance 0.1, summed to a sine of amplitude 0.1 with frequency 0.16 Hz, to prevent nonlinear friction effects, and an offset of 0.32 V. The data acquisition is done using Matlab Simulink and Dspace, see Appendix B.

To validate the frequency response measurement the coherence method is used, see figure 4.2. This shows the correlation between the input and output signals measured over the range of excited frequencies. If the correlation is 1 then the relation between the input and output signals is linear and the measurements can be used to fit a linear model.

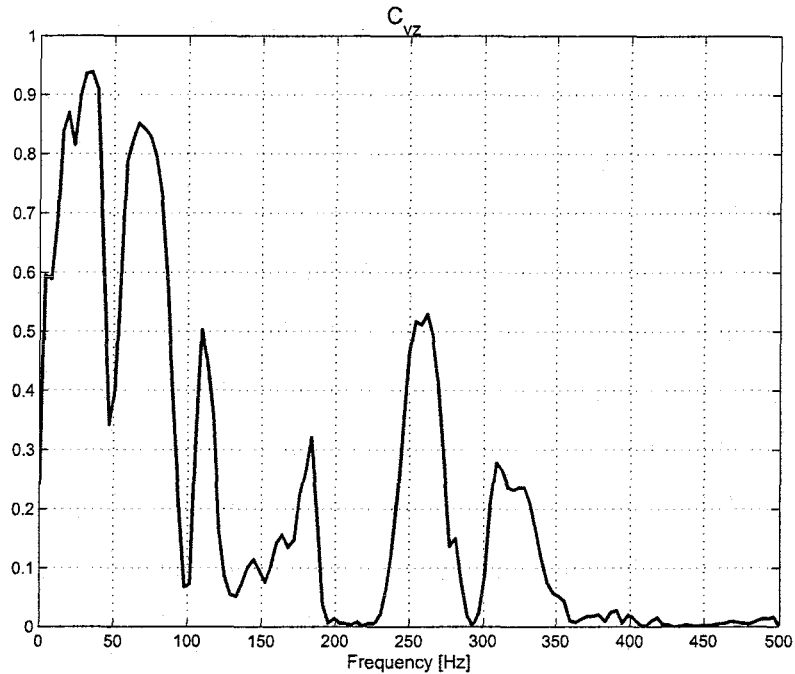


Figure 4.2: Coherence

According to figure (4.2), the data obtained at low frequencies have a coherence near to 1, which means that the low frequent dynamics of the system are well described by the fitted model obtained using the FRF measurements, see figure (4.3). The high frequencies are not well described and further study has to be done, see recommendations in Chapter 5.

The data processing is done using Matlab routines like transfer function estimate (TFE). This routine gives an estimation of the frequency response according to the measured data. The obtained frequency response is shown at figure 4.3:

Looking at the bode plot in figure 4.3, the system shows at low frequencies a constant gain value, that starts to fall at 10 Hz. To identify the reason of this, an estimation of the stiffness is performed using Hooke's law. Placing weights on the top of the voice coil the probe will move. Measuring this displacement and using the relation in equation (4.5), the stiffness is obtained. Besides it is the slope of the curve in figure 4.4.

$$F(N) = -K * z \tag{4.5}$$

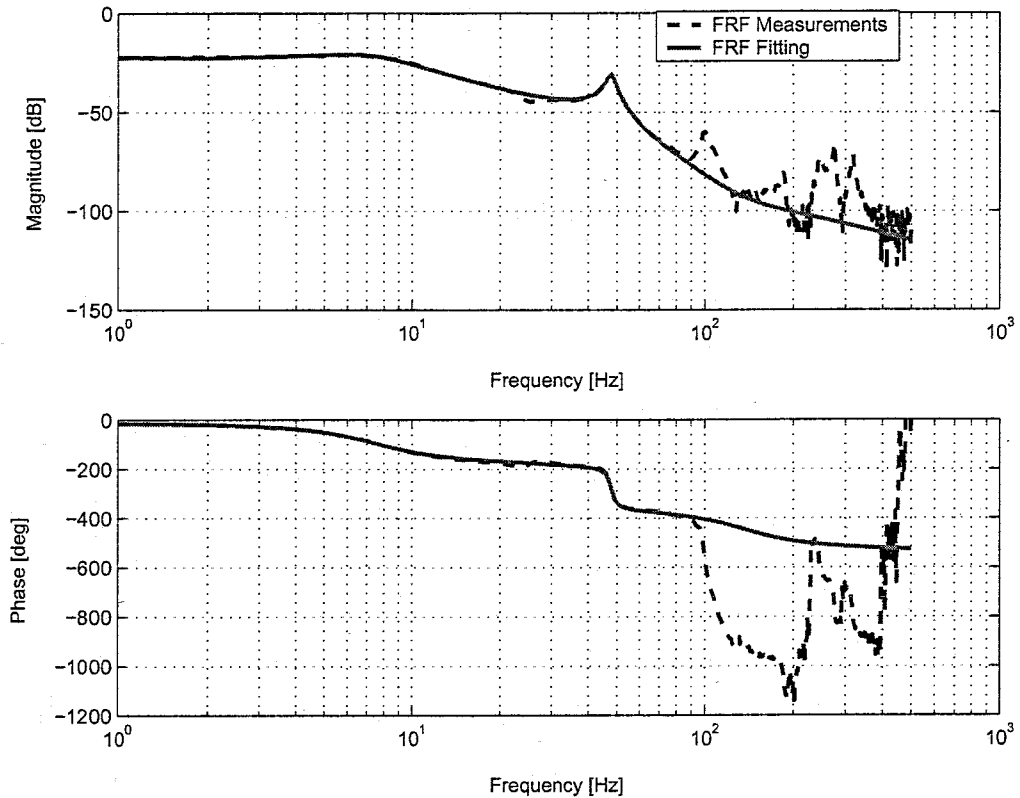


Figure 4.3: Frequency response of the plant

Knowing the stiffness and the mass of the system, it is possible to calculate the resonance frequency according to equation (4.6):

$$\omega \text{ [rad/s]} = \sqrt{\frac{K}{M}} = \sqrt{\frac{828.98}{0.66}} = 35.4 \quad (4.6)$$

The resonance frequency is at 5.64 Hz, where the system starts to feel the mass as shown by the phase drop to 180° in the FRF.

4.2 Control design

After studying the frequency response measurements and having the estimated transfer function (FRF fitting) plotted in figure 4.3, the design of the controller is done. The controller requirements are:

- ✓Bandwidth of 5 Hz (low bandwidth)
- ✓Steady state error smaller than 0.1 mm
- ✓Sensitivity smaller than 6 dB.

The controller is a PI which is used to achieve the required bandwidth as well as to reduce the steady state error. The controller is given by:

$$C = 5 \frac{s + 10}{s} \quad (4.7)$$

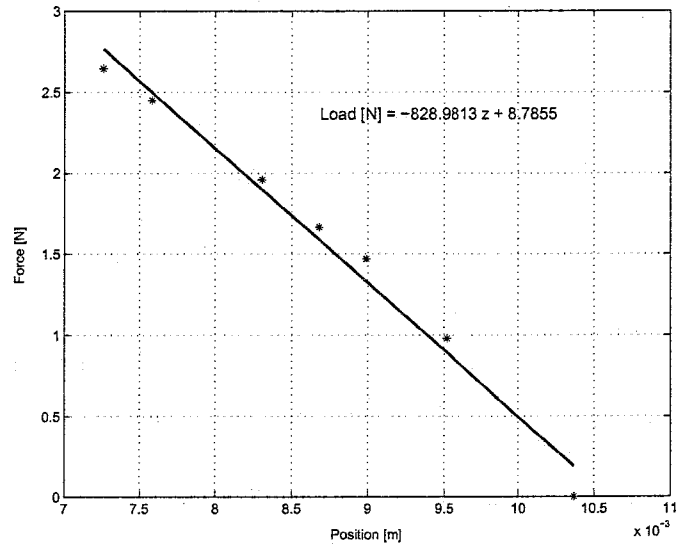


Figure 4.4: Stiffness estimation

The open loop using the FRF measurements is shown in figure 4.5, it has a bandwidth of 5 Hz, which fulfills the requirement.

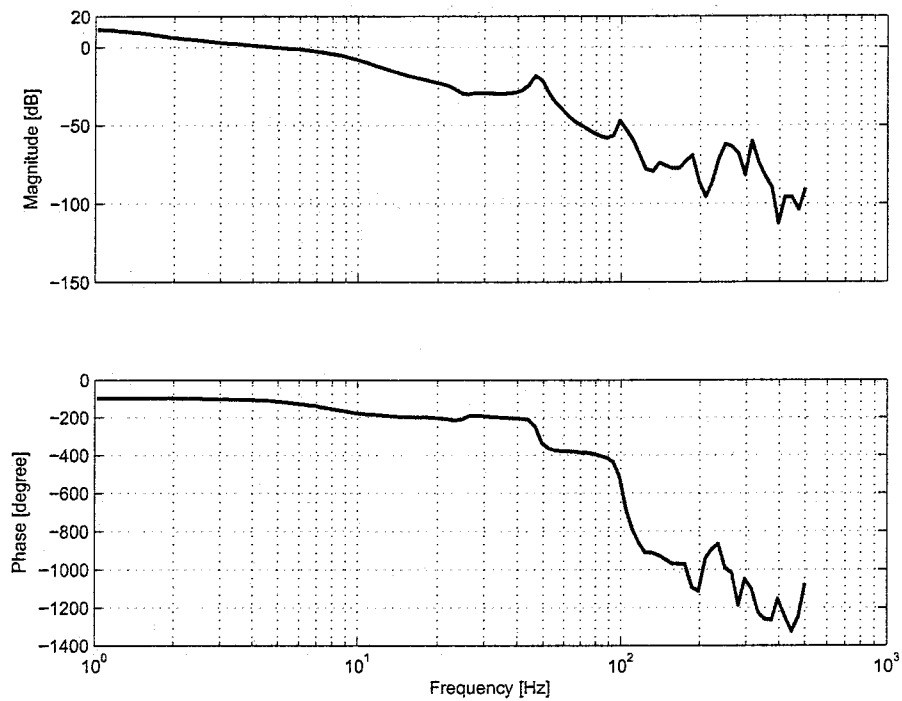


Figure 4.5: Open Loop

To check the benefits of the feedback system, the sensitivity function is studied showing that the controller has been designed to have it small at low frequencies, and with a peak value of 5.74 dB, see figure (4.6).

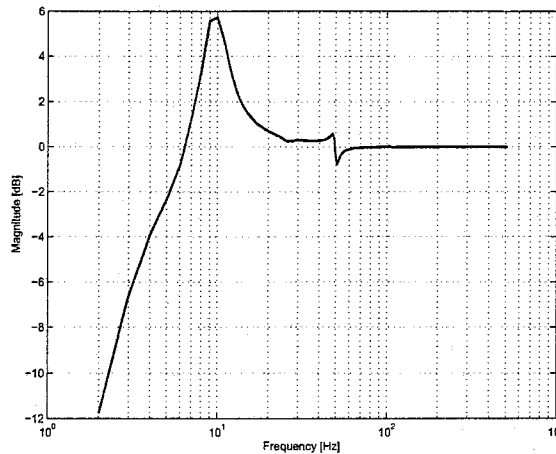


Figure 4.6: Sensitivity

Finally, the controller is implemented in the real set up using Matlab Simulink and Dspace, see Appendix B. Some results and simulations after implementation are shown in the next section.

4.3 Experimental Results

The measurements and simulations are shown in figure 4.7 and 4.8. The reference trajectory is obtained using a constant reference velocity which is integrated to get the reference position. To avoid infinite integral action, a saturation block is used in the Simulink model to limit the maximum position (stroke). In figure 4.7, the velocity is $2 \cdot 10^{-4}$ m/s and in figure 4.8 the velocity is $4 \cdot 10^{-4}$ m/s.

Looking at figure 4.7 on the left side the simulated reference position, the control voltage and the error are shown and can be compared with the measurements on the right side. It is visible that the reference position is achieved (plot b). Comparing the reference position and the measured position, the difference between the signals is probably due to coulomb friction. It is observed that when the motor starts to move a stick slip effect is present. As result, is that the controller effort cannot influence satisfactory the control input to avoid this phenomenon. At the present work it is assumed that the coulomb friction causes the difference between the signals. Nevertheless, a further research to examine the causes of the difference between the signals is recommended.

The transient tracking error (plot f) is bigger than the desired value of 0.1 mm. Since the steady state error is zero, the integral action of the controller fulfills its goal.

The measurements for a constant velocity of $4 \cdot 10^{-4}$ m/s are given in figure 4.8, it is visible that the position time response (plot b) is faster than in the previous case, and the control voltage is larger than in the simulations (plots c and d), it demonstrates that the motor is asked to act faster to changes in the position.

The designed controller fulfils the requirements of having a bandwidth 5 Hz, a sensitivity peak of 5.74 dB and a zero steady state error. However, the transient response of the tracking error is bigger than 0.1 mm, which exceeds the requirement. It is expected that further improvements in the controller, like addition of friction compensation, could lead to better performance of the positioning system.

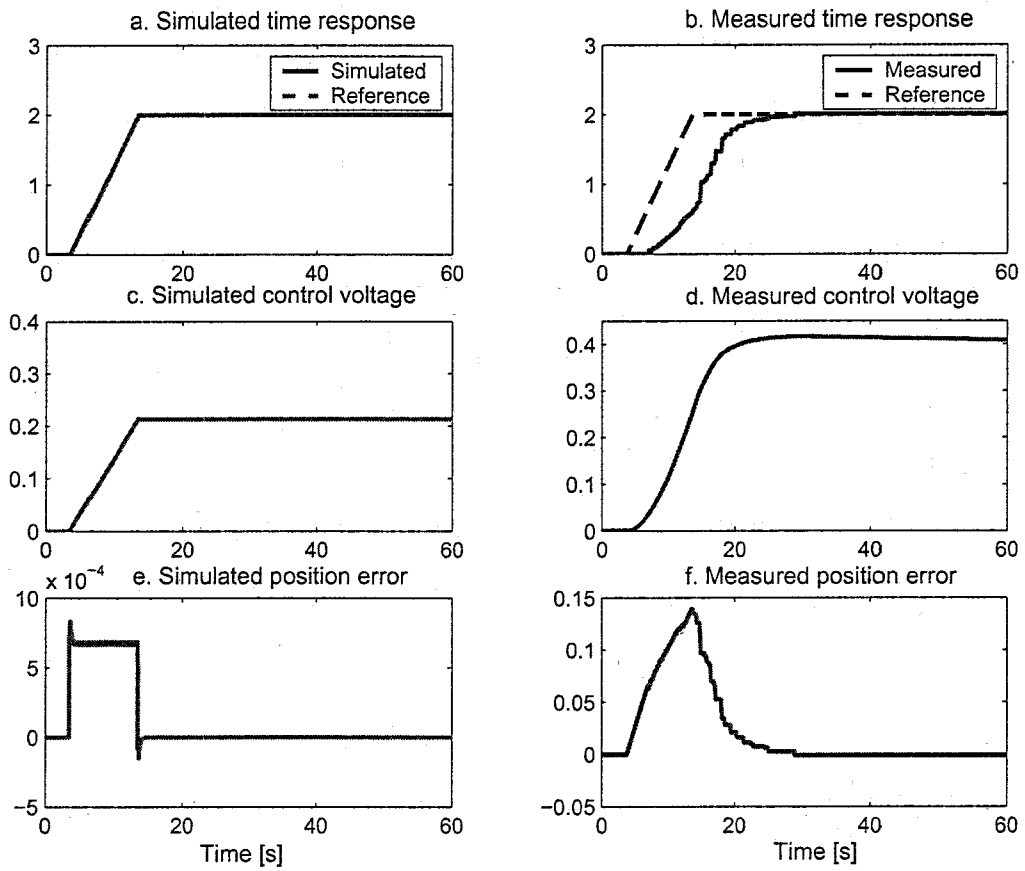


Figure 4.7: Measurements and Simulations with constant velocity of $2 * 10^{-4}$ m/s

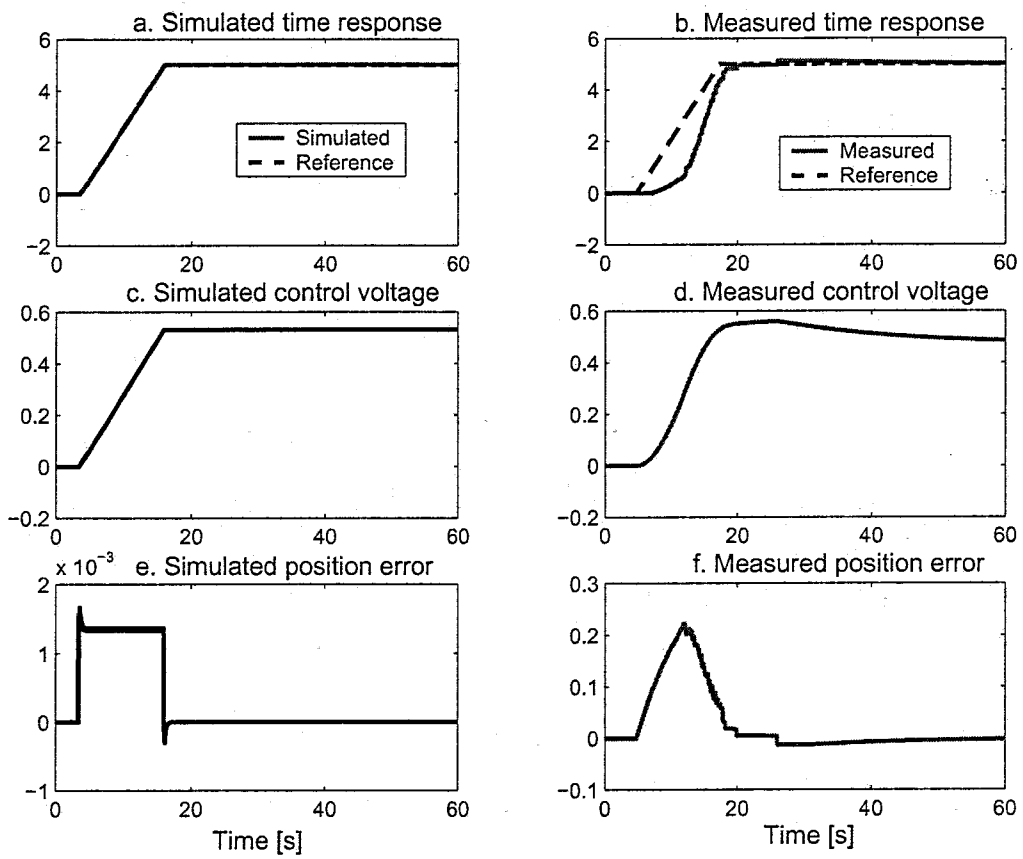


Figure 4.8: Measurements and Simulations with constant velocity of 4×10^{-4} m/s

Chapter 5

Conclusions and Recommendations

The development of apparatus capable to avoid and/or reduce harmful effects in the patients or living specimens is important. To that extent, the introduction of plasma technique in medicine is an innovative and effective development under test. The present work is aimed to improve the positioning system for this technique called *the plasma needle probe*.

The positioning system for the plasma needle probe includes means to measure and control the distance between the needle tip and the cell sample. After studying several alternatives for the motion, guiding and measuring systems for the plasma needle probe, the selected designed is composed of: a voice coil actuator, capable to move forward and backwards controlling the position of the needle probe; A leaf spring arrangement used as guiding system, which fixes 5 DOF of the needle probe; An inductive sensor, which measures the distance between the needle tip and the sensor's active face. The guiding system could be improved using a flexible connection between the actuator and the interface box. This flexible connection has two main goals: releasing one DOF, to allow the motor to have a straight translation in z-direction and the second one, to compensate the rotational effect of the leaf spring (it is demonstrated in section Material Selection equation (3.7)).

To control the position of the needle, the design of the control loop is done. FRF measurements of the system are obtained and used to design the controller, which is used to prove that the system can control the position of the plasma needle within the specifications. The results of the implementation of the controller are satisfactory. However, improvements in the controller for friction compensation have to be done.

Moreover, as a future development in the design of the positioning system, it is recommended to validate the usability of the "Smart Positioning Sensor" design by van der Laan [18]. It can be done, performing FRF measurements using the smart sensor, and comparing this results with the FRF measurements performed using the inductive sensor. If the coherence of the new measurements has a value near to 1, the smart sensor can be used to measure the distance from the needle tip to the cell sample.

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Appendix A

Material properties

| Material | Young's Modulus 10^9 N/m^2 | Ultimate strength $S_u 10^6 \text{ N/m}^2$ | Yield Strength $S_y 10^6 \text{ N/m}^2$ |
|----------------------------|---|---|--|
| Structural Steel ASTM-A361 | 200 | 400 | 250 |
| Aluminium | 70 | 110 | 95 |
| AISI 316 | 193 | 515 | 200 |

Table A.1: Material properties

✓ Torsion equations:

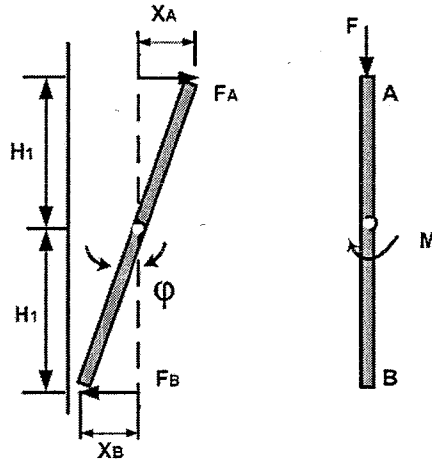


Figure A.1: Leaf spring torsion

According to the figure A.1:

$$F_B = C_{xx} * X_B \implies X_B = \frac{F_B}{C_{xx}} \quad (\text{A.1})$$

$$F_A = -C_{xx} * X_A \implies X_A = -\frac{F_A}{C_{xx}}$$

$$\varphi = \frac{X_B + X_A}{2 * H_1} = \frac{F_B - F_A}{2 * C_{xx} * H_1} \quad (\text{A.2})$$

Knowing that:

$$F_B = \frac{M}{2 * H_1} \quad (\text{A.3})$$

$$F_A = -\frac{M}{2 * H_1}$$

Replacing equation A.3 in A.2:

$$\varphi = \frac{M}{2 * H_1^2 * C_{xx}} \quad (\text{A.4})$$

The torsional stiffness is:

$$K = \frac{M}{\varphi} \quad (\text{A.5})$$

Replacing A.4 in A.5 and after some manipulations:

$$K = 2 * H_1^2 * C_{xx} \quad (\text{A.6})$$

A.1 Support structure

The stiffness of the systems is obtained calculating the ratio of the total force acting in the system over the maximum stroke of 10 mm.

| | | |
|---------------------------|-------------|---------|
| Gravitational force | F_g | 0.9 |
| Voice coil maximum force | F | 10 |
| Leaf spring force | F_z | 0.1 |
| Compensation spring force | F_s | 2.5 |
| Total force | F_T [N] | 13.5 |
| Estimated stiffness | C_e [N/m] | 1350.11 |

Table A.2: Stiffness of the system

| | | |
|-------------------|------|--------|
| Material weight | [Kg] | 0.1677 |
| Probe | [Kg] | 0.09 |
| Support probe | [Kg] | 0.116 |
| Springs | [Kg] | 0.03 |
| Voice coil | [Kg] | 0.255 |
| <i>Total Mass</i> | [Kg] | 0.66 |
| F_p | [N] | 6.46 |
| $F_p * 20\%^2$ | [N] | 7.75 |

Table A.3: Support structure

| | | |
|----------------|----------------------|----------------------|
| F | [N] | 7.75 |
| a | [m] | 0.0785 |
| b | [m] | 0.025 |
| l | [m] | 0.1035 |
| I | [Kg/m ²] | $5.00 \cdot 10^{-8}$ |
| δ_{max} | [mm] | 0.0044 |

Table A.4: Beam deflection

Appendix B

Voice coil specifications

| | | | |
|--|--------|---------------|--|
| Basic application data | | | |
| Load force | 0.5 | N | |
| Friction force | 0.002 | N | The surfaces in contact are the shaft of the motor and the guide. |
| Load mass | 90 | g | Mass of the probe and the connectors . |
| Total stroke | 10 | mm | |
| Type of movement | 1 | | 1: point-to-point positioning 2: regular oscillating movement |
| Move time | 5 | s | Shortest time for maximum displacement of the load |
| Dwell time | 10 | s | Time between 2 moves. Take the worst case: shortest dwell time. |
| Time of movement | 2 | s | 1: triangular speed curve (acceleration during 1/2 move time and deceleration during 1/2 move time) |
| Minimum Peak Force required | 0.60 | N | This is a preliminary underestimated of the required Peak Force. It does not take into account the actuator coil mass. |
| Actuator candidate: Densitron | VM4032 | | Specifications in the Densitron catalogue |
| Mass of the voice coil moving member | 25 | g | |
| Thermal resistance | 8.40 | $^{\circ}C/W$ | |
| K _F (=K _B) | 10.5 | N/A | Force Sensitivity of the actuator candidate at (25 $^{\circ}C$) |
| Coil resistance | 12.80 | ohm | At ambient temperature (25 $^{\circ}C$) |
| Max. coil temperature | 155 | $^{\circ}C$ | Standard value |
| Inductance Ldi/dt | 4.60 | V | Estimated (usually 1V max) |
| K _F (=K _B) at application ambient temperature | 10.50 | N/A | Force Sensitivity recalculated at the ambient temperature of the application |
| Coil resistance at ambient temperature | 12.80 | ohm | |
| Coil resistance at maximum winding temperature | 19.21 | ohm | |
| Continuous Stall Force | 9.42 | N | Recalculated at the ambient temperature of the application. |

| | | |
|---|--------|---------|
| Average speed | 0.0020 | m/s |
| Maximum speed | 0.0027 | m/s |
| Maximum acceleration | 0.0021 | m/s^2 |
| Acceleration force | 0.0002 | N |
| Safety margin | 20 % | |
| Peak Force required | 0.60 | N |
| RMS force required | 0.30 | N |
| Actuator Continuous Stall Force required | 0.30 | N |
| Required supply | | |
| Minimum bus voltage required | 5.73 | V |

Table B.1: Calculation of the Voice Coil Motor

Appendix C

Control scheme implementation in Simulink

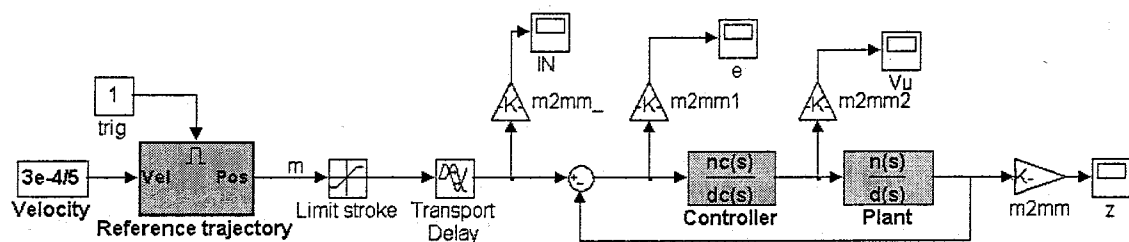


Figure C.1: Simulink Model for Dspace connection

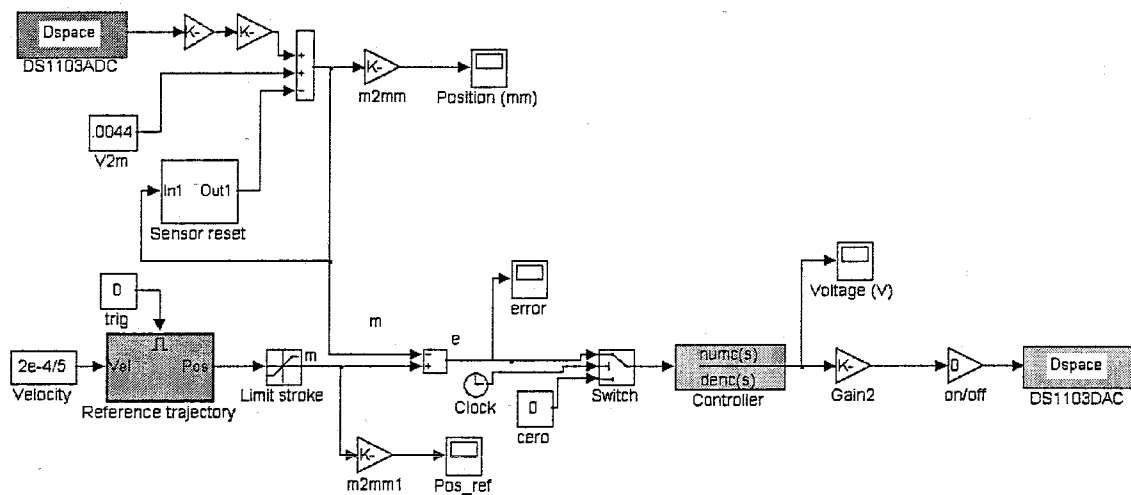
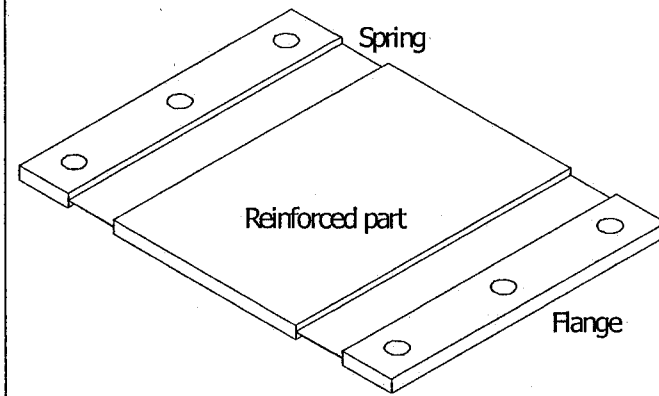
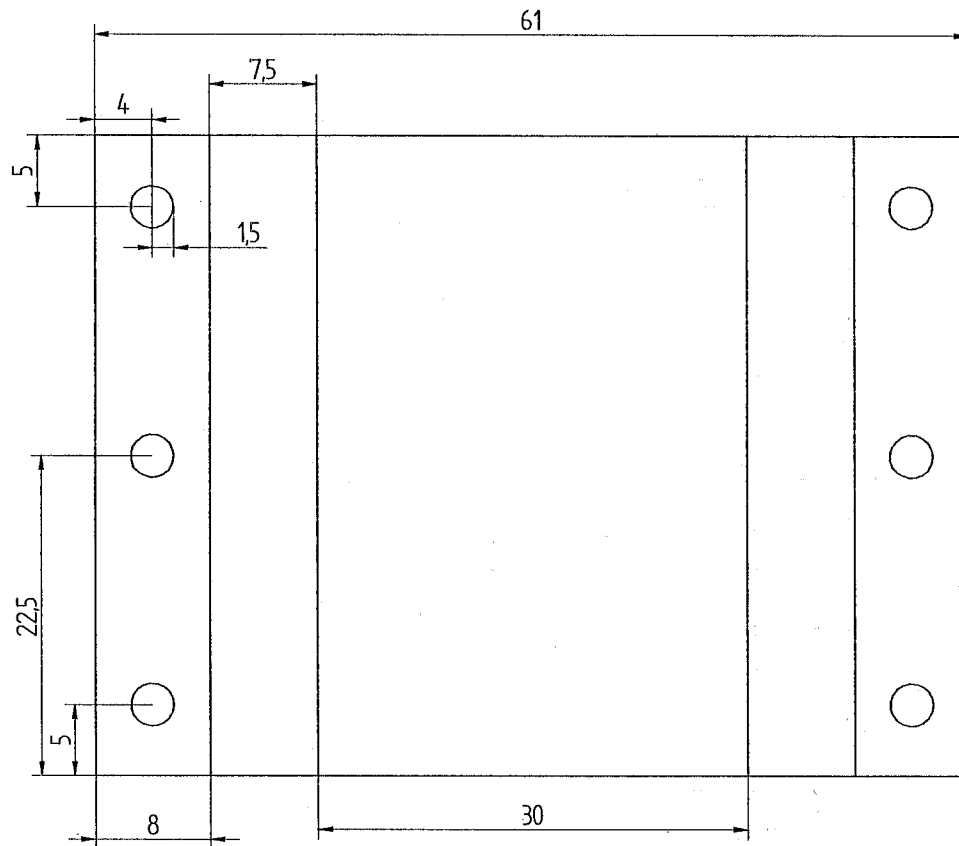


Figure C.2: Simulink Model for Dspace connection

Appendix D

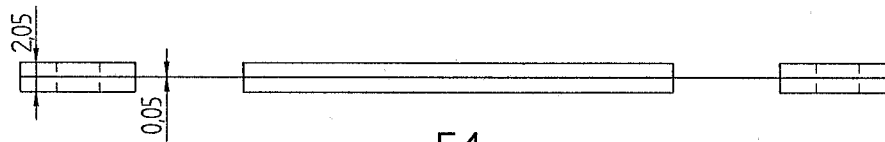
Drawings

38



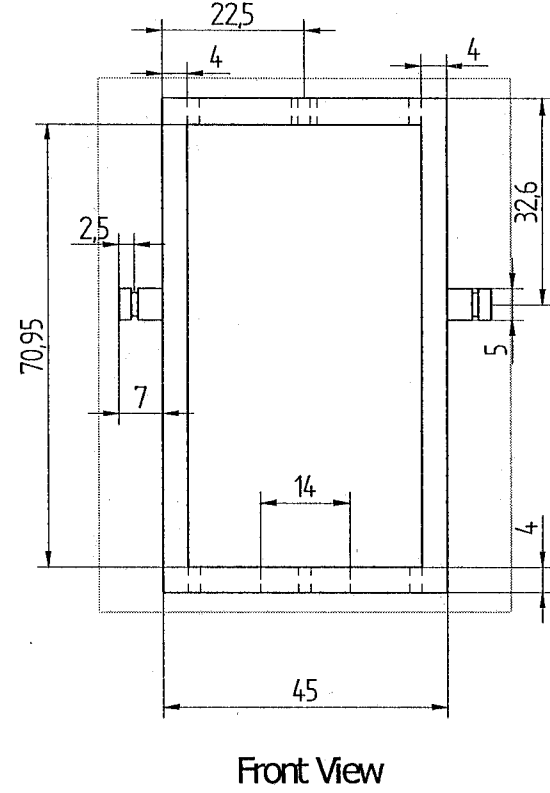
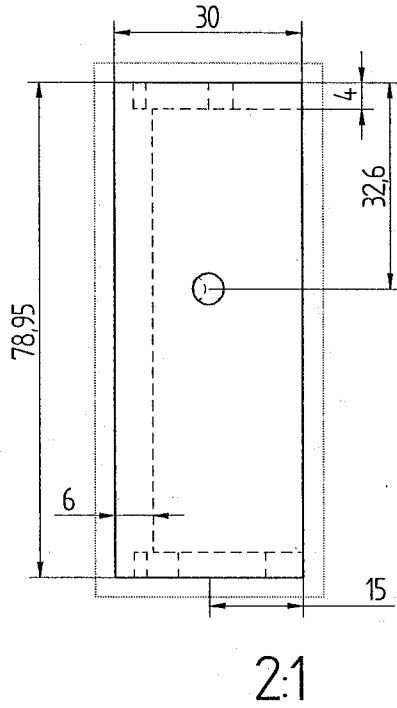
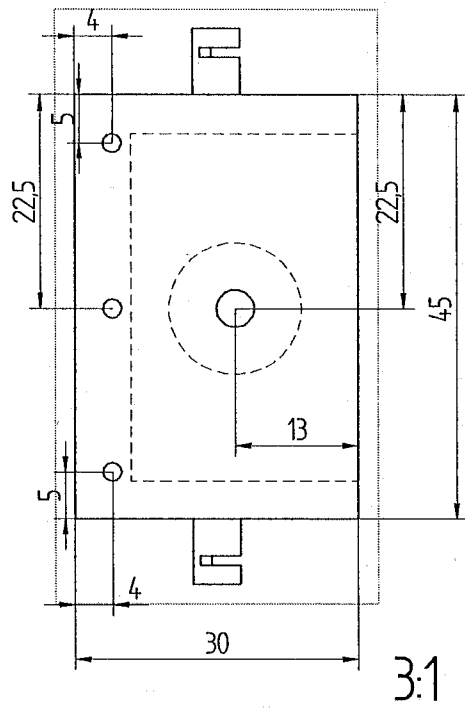
5:1

Spring Material:
Stainelss Steel
ATSI 316
Reinforced part:
Aluminium 1 mm



5:1

Figure D.1: Leaf spring



Material: Aluminium

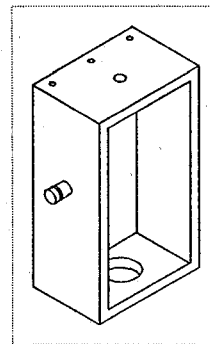


Figure D.2: Box

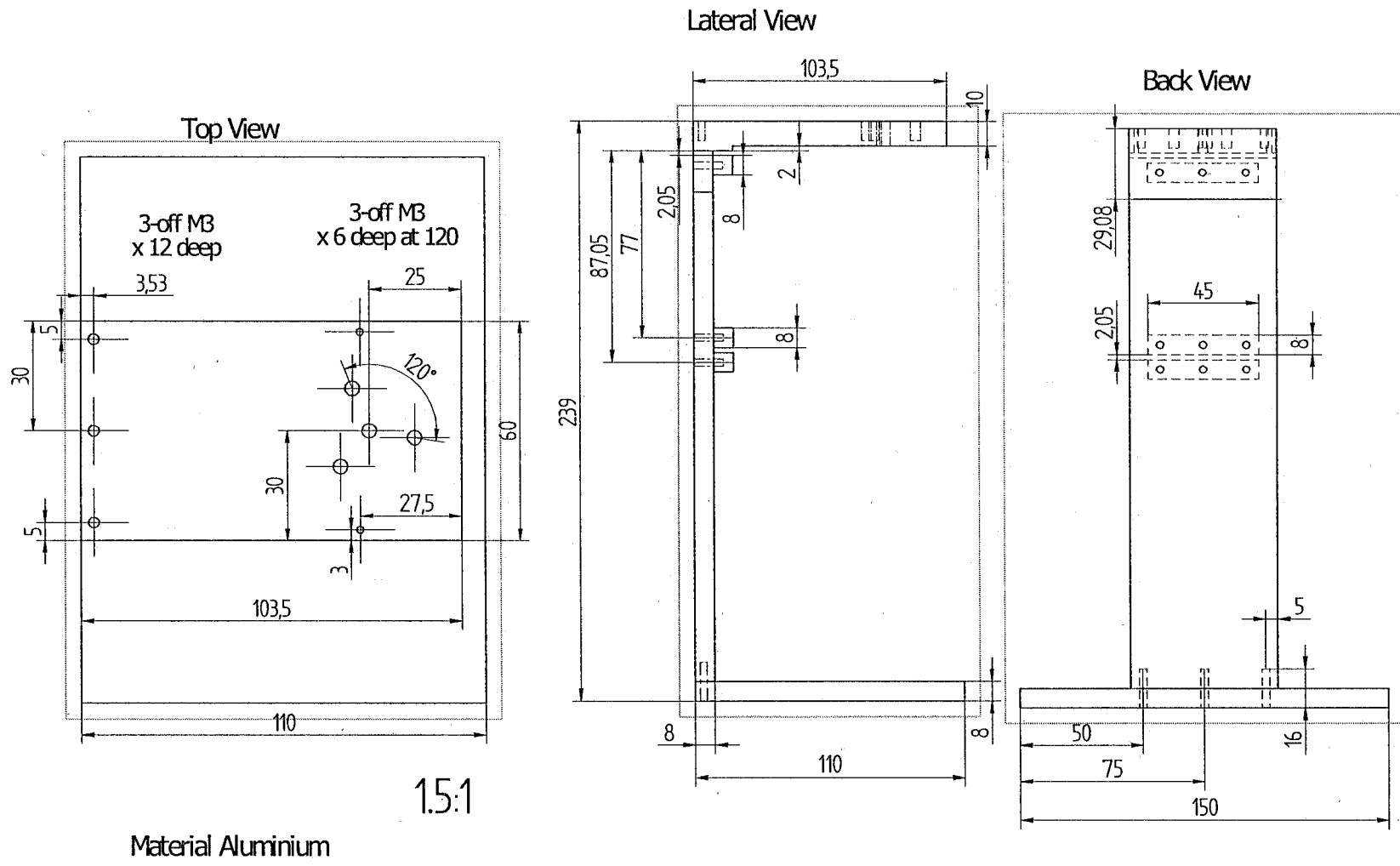


Figure D.3: Support structure