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Design of 3D plasma needle manipulation

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Design for 3D Plasma Needle Manipulation

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Abstract

The type of plasma source that is used for the plasma needle can be described as a low temperature non-equilibrium capacitive coupled radio frequent discharge. Discharges excited and sustained by high-frequency electromagnetic fields are classified as radio-frequent (RF) or microwave (MW) discharges. They usually operate in frequencies of respectively $1 - 100$ MHz and 2.45 GHz. With a capacitive geometry the electrical field is created by voltage difference. This is known as a Capacitively Coupled Plasma (CCP).
This new plasma source is capable of :

- detaching cells,
- reattaching cells,
- transferring cells,
- bacterial decontamination,
- inactivation of bacteria,
- inactivation of spores,
- causing some of the cells to undergo apoptosis.

The plasma needle can be used for various medical procedures. The dentist will be able to use the needle to disinfect a cavity. For injuries caused by burn, the wounds can be disinfected without making contact. But for now the plasma needle is still in experimental stages. It is tested on skin cells which are placed in small compartments. The plasma has to be positioned with an accuracy of 10%. When held in the hand this accuracy is hard to reach. To make the experiments easier, faster, more accurate and handsfree, the assignment was given to develop a design for a plasma needle with manipulation in the x,y and z-direction.

So following the assignment, a model and guiding are designed and various x-y guiding possibilities are proposed. The helium supply-tube will be directly connected to the hollow insulated needle which will be able to translate due to the guiding. The guiding exists of radial air bearings. Through the hollow outside cylinder the pressurized air is supplied. This causes the needle to translate relative to the outside tube. For this translation a force is needed. This force is applied by an actuator. In this case a voice coil actuator has been used. For the x-y guiding several options are explored. All of them are suitable , but one of them

will be used namely 3.3. Because the hand or array of compartments shall only have to be positioned in one place, while the x-y and z guiding do the rest.

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Chapter 1

Introduction

This report describes the design of the guidance of a plasma needle. First the concept of plasma and the plasma needle will be explained. The requirements for this design will follow. Next the various concepts of the plasma needle with guidance and the final model that results from these concepts will be elaborated on. Furthermore, principles of the actuator needed for the vertical movement of the plasma needle and the guiding in the horizontal plane will be given. Finally this report concludes with recommendations.

1.1 Plasma

A plasma is identified as a state of matter with enough free charged particles for its dynamics to be dominated by electromagnetic forces. The charged particles are created by inelastic collisions of highly energetic electrons or protons with neutral atoms and molecules. These collisions result in a gaseous or fluid-like mixture that contains ions, free electrons, radicals, (excited) atoms and molecules. It turns out that there is a balance of negative and positive charges inside the plasma. The most remarkable feature of a plasma is its ability to maintain this state of charge neutrality. This is due to the fact that even small variations of this balance lead to large electric fields. The free electrons then rapidly re-establish the charge equilibrium because of their low inertia.

The type of plasma source that this report revolves around can be described as a low temperature non-equilibrium capacitive coupled radio frequent discharge. Low temperature plasma (LTP) or partially ionized gas results from charged particles that are accelerated. These particles then collide with neutral particles, generating new charged particles and hereby causing a cascade of collisions. In a non- equilibrium LTP, the electrons reach a high temperature ($T < 10^5 K$), whereas the ions remain at a lower temperature or even ambient temperature. The low energy of the ions is caused by the small energy loss of the light electrons in the elastic collisions with the heavy neutrals and ions, according to the conservation of momentum and energy. Discharges excited and sustained by high-frequency electromagnetic fields are classified as radio-frequent (RF) or microwave (MW) discharges. They usually operate in frequencies of respectively $1 - 100$ MHz and 2.45 GHz. The physical set-up of the

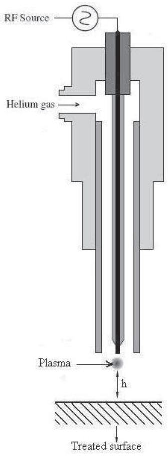


Figure 1.1: The original plasmaneedle

plasma source defines the power coupling of the RF discharge. With a capacitive geometry (for example parallel plate electrodes) the electrical field is created by voltage difference. This is known as a Capacitively Coupled Plasma (CCP)[8].

1.2 The plasma needle

The original device consists of a metal wire with a sharpened point which functions as an electrode for the electrical field. The wire is placed coaxially in a grounded metal tube, through which the helium gas flows. Insulation of the wire assures that the plasma is generated only at the tip. The plasma is created by the discharge of helium as a result of the applied radio frequency of 13.56 MHz. The discharge is excited and sustained in helium at atmospheric pressure. Other noble gasses have also proven to be effective.

This new plasma source is capable of detaching, reattaching or transferring cells. It is capable of bacterial decontamination, it has interactions that leads to inactivation of several types of bacteria and even spores and a small percentage of the cells even underwent apoptosis. The small dimension of the plasma allows local cell detachment in a 100 μm range. Despite its reactivity, the plasma does not cause (thermal) damage like necrosis to sensitive biological materials when operated properly. [8]

1.3 Purpose of this report

The plasma needle can be used for various medical procedures. The dentist will be able to use the needle to disinfect a cavity. For injuries caused by burn, the wounds can be disinfected without making contact. But for now the plasma needle is still in experimental stages. It is tested on skin cells which are placed in an array of small compartments. The plasma has to be positioned with an accuracy of 10%. When held in the hand this accuracy is hard to reach. To make the experiments easier, faster, more accurate and handsfree, the assignment was given to develop a design for a plasma needle with manipulation in the x,y and z-direction.

Chapter 2

The Requirements

The plasma is visible as a spherical glow with an average dimension of one millimeter. The distance from the needle tip to the surface that has to be treated is called the gap. This is one of the factors that determine the amount of reactive species acting on the surface and thus the effect of the plasma. This amount decreases as the gap width r increases, because of diffusion. It is expected that the flux of radicals scale consequently with $1/r^2$. However, there is convection of species due to the gas flow towards the surface and therefore their number is somewhat increased. The minimum precision of the gap that influences the plasma reactivity has been estimated. It seems that the number of species that interact with the surface increases with 10% for every 0.1 millimeter decrease in gap width (within the 2 mm range).

The desired accuracy of the gap and thus of the z-stroke is 10%. The assumption has been made that the needle will be used to treat plane surfaces with a depth variation in the z-direction of a maximum of 2 mm.

Also the accuracy desired to position the needle in the horizontal or x-y plane is 10%. The stroke that has to be made in the x and y direction has to be at least 40 mm.

At a distance of 2 mm from the treated area, the plasma has a range of 8 mm. This area has to be treated for 60 seconds.

The velocity of the helium flow that is needed around the needle has to be 1 m/s for the gas to partially ionize. In the original needle described above the helium flow is equal to 2.0 liters per minute. This constant supply is sustained by a flow controller.

The radio frequency needed to discharge helium has to equal 13.56 MHz.

Table 2.1: Requirements for the design of the manipulation of the plasma needle

Accuracy gap	10	%
Accuracy z-stroke	10	%
Accuracy x-y stroke	10	%
Depth variation z-direction	2	mm
Magnitude x-stroke	40	mm
Magnitude y-stroke	40	mm
Velocity helium flow around needle	1	m/s
Radio frequency	13.56	MHz

Chapter 3

Design of the z guidance of the plasma needle

3.1 Introduction

For movement in the z-direction aerostatic bearings will be used. Radial bearings will be supplied with air or helium gas to accomplish the guidance. In this chapter the functioning of aerostatic bearings will be explained, along with the advantages and disadvantages of these bearings. Furthermore, three designs of the plasma needle will be explained. As will be the application of the bearings.

3.2 Guidance based on a syringe

A syringe is used as a reference for the design of the guiding of the plasma needle. Basically a syringe consists of a piston inside a hollow cylinder. When a force is axially applied to the piston, it moves inside the cylinder. The guiding of this movement is accomplished by rubber piston rings. At the same time these piston rings are used to seal the gap between the piston and the cylinder wall to prevent the liquid from escaping.

The idea arose to substitute the piston for the plasma needle. In this case the needle is a hollow cylinder made from a polymer, through which the helium will flow. The hollow outer cylinder from this point on called the tube, is also made from a polymer. A polymer was chosen as material to maintain a low mass. At the end of the inner cylinder there will be a piece of metal that could be screwed onto the polymer needle. From the outside the electricity could be provided by a wire. Or that wire could run through the tube wall and only at the end of the tube be connected to the needle. Another possibility is to let an insulated wire run through the needle and only at the mouthpiece of the needle would there be no isolation, so that the plasma can form. The idea of using rubber as guiding is rejected because of the great amount of friction between the rubber piston rings and the hollow cylinder. Other guiding methods include elastic guidance and bearings. Because elastic guidance is already

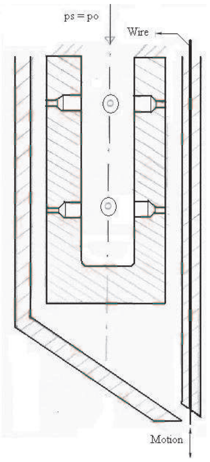


Figure 3.1: Model based on a syringe. The wire runs through the tube wall, with only a tip appearing on the bottom of the tube. This is where the helium from the guidance will flow past.

being examined [7], guidance by bearings will be examined. Because ball-bearings would also cause friction, aerostatic bearings were the next alternative.

3.3 Aerostatic Bearings

Aerostatic bearings are bearings that use (pressurized) gas, in most cases pressurized air, as film between the surfaces. Air at the supply pressure $p_s = p0$ enters the nozzle through a restrictor. The restriction provides an decrease in pressure (pressure drop) between the pressure supplied $p0$ and the gap pressure p_d. (See Figure 3.2). This gives the possibility to compensate for a change in loading or in other words the bearing has stiffness.

There are two types of compensations, inherent compensated and orifice compensated bearings(See Figure 3.2). The dependency on h is what makes bearings with inherent stiffness up to one third that of the orifice ones.

Pneumatic hammer is an instability in which the pressure in the bearing becomes oscillatory, and the whole bearing resonates. Inherently compensated bearings have no pneumatic hammer due to their no pocket design. This is based on the compressibility of gases and the resulting delay between changes in the bearing gap(clearance) and the response to these changes. Because of this, orifice compensated bearings are less stable than inherent compensated bearings and that is why the latter are most frequently used.

Aerostatic bearings have the following advantages:

- Minimal static, running and stopping friction, due to the very low viscosity of gasses. A thin film of pressurized gas separates the two surfaces. Because the object is floating on a thin layer of air, or gas, the friction is very small.

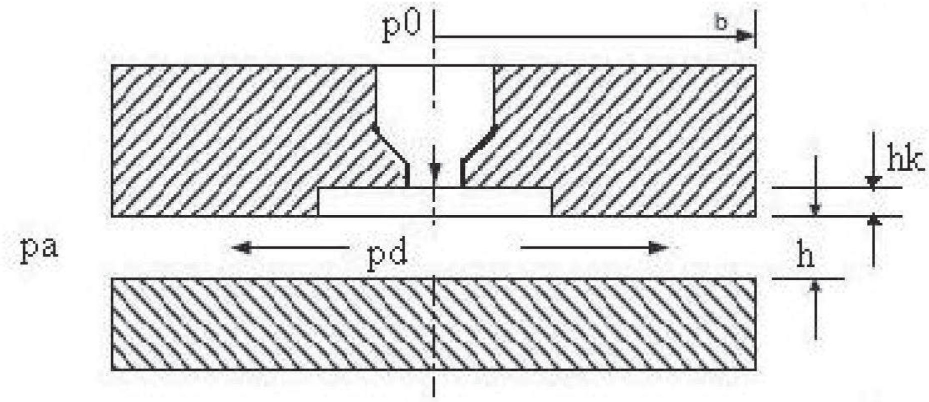


Figure 3.2: Aerostatic bearing: Inherent compensated if hk = 0 or hk « h. Otherwise orifice compensated.

- Also there is no wear as well as no direct transfer of vibrations, because there is no contact between the surfaces. This leads to high repeatability. The advantage of zero wear can also be seen in the long life span of such bearings if these are properly used and designed.
- A high accuracy over a wide speed range, because the components are manufactured with extremely tight tolerances and because of the air film's averaging effects.
- The precision achievable is only limited by the abilities of the motor, the controller and the encoder.
- No oil or grease lubrication.
- Loads are supported at zero speed and zero friction. The pressure inside the gap creates the load carrying properties which are limited only by the available supply line pressure and material strength.
- With a correct design, very high stiffness can be obtained.

Aerostatic bearings have the following disadvantages:

- An external pressure source is required to create the air film.
- The thin layer of air used is in the order of about $5 - 30\mu$m. The manufacturing cost of such small clearances is very high.
- The manufacturing of these clearances is also very difficult.
- Instability possibility when orifice compensated.

[3], [6], [5]

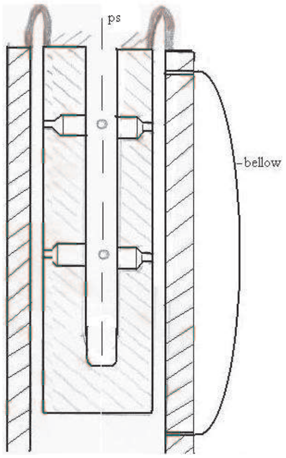


Figure 3.3: Relative tube movement with helium recycling. The rubber seal prevent helium from being wasted, while the bellow relieves the pressure that builds up in the seal.

3.3.1 Model 1: Aerostatic guidance with moving helium tube

In the design process the possibility of using helium instead of air is considered. Because helium was needed to form plasma and by supplying the same helium gas to the bearings a compressor cylinder for the air wouldn't be required. So instead of two tanks and two supply-lines, one containing helium and the other air, now only a helium tank is required. The most important difference between helium and air is the density. The density of air is seven times as much as that of helium gas.

Next the needle would be placed inside a hollow cylinder. The wire used for the needle would be made out of metal with a good electrical guiding coefficient and insulated on the outside by a polymer. The insulation would be needed so that people wouldn't get shocked by the electric current when handeling or being treated by the needle. Secondly, it is needed to keep the wire from turning into an antenna. When applying a radio frequent signal to a wire this causes a transmission [7]. Third, to see to it that the helium only discharges at the end of the needle.

In a syringe a force is put on the piston so it can move up and down in the tube. But if the same principle was used in this model then the helium supply-tube would have to move up and down with the needle, because it would be directly linked to the needle. Moving the supply-tube could cause the needle to tilt and create an error in the position of the needle on the skin. Also the needle could collide with the outer cylinder.

When the aerostatic bearing doesn't provide sufficient stiffness tilting of the needle could cause an error bigger than the maximum of 10% that was demanded. To prevent this from happening the stiffness of the bearings would have to be even higher. A solution to this problem would be to fix the needle and let the tube translate in the z-direction. (See Figure 3.1). This way the problem of the moving helium tube would be solved.

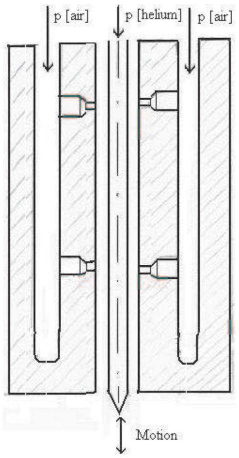


Figure 3.4: Needle movement. Helium flows through the needle. Pressurized air is supplied to the bearings, through the hollow wall.

3.3.2 Model 2: Aerostatic guidance with moving outer cylinder

In Figure 3.1 the helium can escape via two routes. Through the hole on the lower side of the tube, where the needle would be. And through the other end of the outer tube. To stop the helium from being waisted a soft rubber seal would be placed on the top between the piston and the outer tube. When movement takes place, the rubber seal also moves. A problem that then could occur is that the helium quantity on the rubber side would increase, causing the pressure to increase and thus, because the rubber is soft enough, blowing the rubber up like a balloon. Else, if the stiffness of the rubber was higher, the pressure could get to a point that it would cause the outer tube to move upwards. The solution to this problem is to connect a tube from the rubber end to the needle end and in this manner the pressure could be annulled. (See Figure 3.3)

3.3.3 Needle movement and air bearings

An alternative to the above is to let the needle, translate inside the tube. The wall of the tube is also hollow but open on only one side, the upper side. This side is fixed and connected to the helium supply-tube. The problem here is the difficulty to position the actuator. The possibility exists not to make the opening on the upper side of the cylinder, but to make an opening on the side. This way the helium could still get through and the actuator could be positioned straight above the needle. See Figure 3.4. Another possibility is to let the helium supply-tube be directly connected to a hollow needle, which can translate inside the hollow cylinder. Another supply-tube, containing air, could then be attached to the hollow wall of the cylinder. This way the needle is guided using air bearings instead of helium.

3.4 Conclusion

The models described in this chapter give a number of possibilities for guidance based on aerostatic bearings. For the film needed between the 2 surfaces air as well as helium are an option. In the next chapter there will be decided which model is sufficient enough.

Chapter 4

Guidance of the plasma needle: helium and air bearings

4.1 Introduction

After considering all of the models in the previous chapter, the final model will be chosen. Orifice as well as inherent compensated bearings will be calculated to find out which will be the best for this model. This will be done by comparing the total gas flow and stability. There are two options when it comes to gas supply for these bearings: air, most commonly used, and helium. For both of these the results will be given and compared. A conclusion will then be drawn from this data.

4.2 Stiffness calculations

The aerostatic bearings used are radial bearings. The following assumptions have been made to perform the required calculations:

- n = 8 supply-holes. Eight supply-holes are needed to prevent as much rotation as possible, to have a high total stiffness and to establish force equilibrium.
- N = 8 bearing bases. Naturally eight bearing bases are needed, because there are 8 supply-holes.

Assume that the (outer) diameter of the needle (or inner cylinder) D equals 1 cm.

$$b = \frac{\pi\ D}{N} \tag{4.1}$$

$$3 < n > \frac{2\pi\ D}{L} \tag{4.2}$$

The width of one base of a bearing: $b = \frac{\pi\ 10^{-2}}{8} = 3.93\ 10^{-3}$ [m] = 3.93 [mm] $\approx$ 4 [mm]
For n equals 8 restriction (or supply) holes: $\frac{2\pi\ D}{L} \leq 8 \Rightarrow L \geq \frac{2\pi\ 10^{-2}}{8} \Leftrightarrow L \geq 7.85 * 10^{-3}$ [m] $\approx$ 8 [mm] These bearings will not be prestressed so the bearing area, the pocket volume and the pressure drop have to be chosen in such a way that the bearing force will equal the optimum bearing power.

At first the choice of bearings was based on maximum stiffness. That's why orifice compensated bearings were initially used. Orifice compensated bearings are 1.5 times stiffer than inherent compensated bearings. But when, after calculations, that proved not to be desirable the decision was made to base the design of the bearings on maximum bearing power and gas usage of the base elements. The amount of air that would have to be supplied was not favorable. (See calculation in appendix ??, orifice compensated for air and helium. In contrast to orifice compensated bearings, inherent compensated bearings are dependant on the gap. This is advantageous because then the air consumption could be additionally controlled by this factor according to:

$$M_{tot} = 0.43 * 10^{-2}\ n\ d\ h\ p_s \tag{4.3}$$

The bearing is inherent compensated if and only if $h < \frac{d}{12}$ and $h_k = 0$, $h_k \approx 0$ or $h_k \ll h$. The diameter of the restrictor has to be: $d \geq 0.4$ mm, because the hole could get clogged when there are particles in the supplied gas that are bigger than 0.4 mm. As result of this measure all bearings, without a pocket, with a gap $h < 40\mu$m will be inherent compensated. The supply pressure will be kept as low as possible, so the gasusage for the guiding will be minimal. For inherent compensated bearings the formulas are only valid in this range: $2 \leq p_s/p_a \leq 7$. So p_s will be approximately 2 atm.

First the optimal gap h_{opt} will be determined. Then the optimal restrictor diameter d_{opt} will be determined. Optimal means that the criterium that was used to determine this value is based on maximum stiffness. As minimum gap 10μm will be used.

$$h^2 = 0.0218 * \frac{L}{D} * \frac{nd}{p_s} \tag{4.4}$$

$h^2 = 0.0218 * \frac{8\ 10^{-3}}{1\ 10^{-2}} * \frac{8\ 0.40\ 10^{-3}}{2\ 10^5}$

$h_{opt} = 16.7\mu$m

$$d = 28.7 * \frac{D}{L}\frac{h^2\ p_s}{n} \tag{4.5}$$

$d_{opt} = 28.7 * \frac{10^{-2}}{8\ 10^{-3}}\frac{(10^-6)^2\ 2\ 10^5}{8}$

$d_{opt} = 89.7\mu$m

According to the criteria mentioned above, d has to be greater than 0.40 mm. Thus is the calculated d_{opt} not valid. The measurements for the restrictor diameter and the gap are respectively 40 mm and 16.7μm The corresponding stiffness S_{tot} and gas usage M_{tot} equal:

$$S_{tot} = 0.53 * (p_s - p_a)\frac{DL}{h} \tag{4.6}$$

$S_{tot} = 0.53 * (2 * 10^5 - 1 * 10_5) * \frac{10^{-2}\ 8*10^{-3}}{16.7*10^{-6}} = 2,54\ 10^5$[N/m].

$M = 0.43 * 10^{-2}\ 8\ 0.40 * 10^{-3}\ 16.6 * 10^{-6}\ 2 * 10^5 = 4.57 * 10^{-5}$ kg/sec per bearing.

$M_{tot} = \frac{2M}{\rho} * 3600 = \frac{2*4.57*10^{-5}}{0.178} * 3600 = 1.85$normal m^3/h = 30.80 l/min helium or 0.27 normal m^3/h = 4.57 l/min air.

A helium usage of 30.80 l/min is very big quantity of that gas. It is not acceptable for so much heliumgas to flow into the room. Though helium isn't a hazard it causes some symptoms, like a very high voice. Heliumgas is not that expensive, but this amount is a waste. If the gap were to be 5μm the usage would be 9.28 l/min. But at this value the clearance is hard and expensive to manufacture. Therefor the guiding will be done with air instead of helium. With this result the model described in 3.3.3 is the one which will be used from now on.

4.3 Error calculations

If the needle gets exposed to an external disturbance, for example a force caused by someone accidently bumping into the needle, the vertical components of the bearing forces 4.9 should balance with the load F that causes an error e. The original gap length h_g equals 16.6 μm. So the error has to be : $e < 16.6\mu m$ Or to be on the safe side:

$$e \leq 15\mu m \tag{4.7}$$

The maximum disturbing force $F = S_{tot} * e = 3.81$[N] The bearing gap [6]:

$$h_j = h_g + e\ \cos\alpha_j \frac{2\pi}{N} \qquad voor j = 1, 2, 3, ..., N \tag{4.8}$$

The bearing force:

$$W_j = W_g - S_L\ e\ \cos j \frac{2\pi}{N} \qquad voor j = 1, 2, 3, ..., N \tag{4.9}$$

Because the disturbance F causes the needle to move out of its balance position, the greatest error is created in h_8 and h_4 (See Figure 4.1). Therefore the largest stiffness has to be produced by base element 4. That is why W_4 is used to determine the largest bearing force needed so that the total of bearingforces in y-direction is in balance with the external force. $W_4 = W_g - S_L^*\ e\ cos 4 \frac{2\pi}{N}$ (See 4.9)

Because there is no chamber in the inherent compensated bearings that are used the length of these chambers a is zero. The static pressure p_s equals 2 bar, because the smallest possible pressure will be used. The formulas that are used are only applicable in the following range: $2 \leq \frac{p_s}{p_a} \leq 7$ The original bearing power for each base element:
$W_g = W_{Li} = 0.35 * (1 + \frac{2a}{3L})(p_s - p_a) * b * L = 1.12$[N]

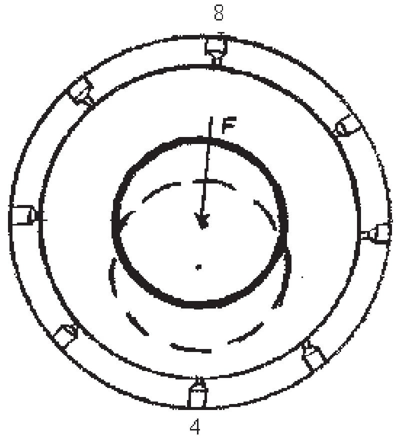


Figure 4.1: Needle out of midstand

$S^*_{Li} = 1.08 * \frac{W_{Li}}{h} = 72.43 * 10^3$ [N/m] per bearing foot.
$W_4 = 1.12 - 72.43 * 10^3 \; 15 * 10^{-6} \; cos\pi = 2.21[N]$
$\sum W_{j_{vert}} = -4.20$ [N] So comparing $\sum W_j$ to F the conclusion can be drawn that the bearing force is in balance with the disturbing force (round off errors kept in mind).

Chapter 5

The Actuation: Voice Coil Actuator

5.1 Introduction Voice Coil Actuators

For the actuation of the needle a voice coil actuator (VCA) will be used. In this chapter the choice for this actuator will be founded. At first the functioning and construction of the VCA will be described. There are two types of voice coil actuators namely the moving-coil and the moving-magnet actuator. The moving-coil motor is most widely used and is more commonly known as voice coil. The advantages and less pleasant characteristics of both kinds will be given. Also a comparison between these two will be provided. At last this chapter will end with the measurements and some formulas with which calculations can be made in the future.

5.2 The voice coil actuator

Voice coil actuators (VCA) have been used primarily as the sources of force in audio loudspeakers, and as drive mechanisms for disk drive read heads. The linear voice coil actuators can now be found in linear and rotary-motion devices requiring linear force or torque and high acceleration (50 g or more) or high-frequency actuation (20 to 400 Hz) [1]. They are characterized by high power densities, high bandwidths, and relatively low pressures.

A voice coil is an electromagnetic actuator that generally consists of one or more coils of wire placed in a magnetic field (See Figure 5.1). The magnetic circuit of the (linear) VCA exists of a yoke and a disk shaped magnet. The magnetic field that is created by this magnet is led to a cylindric gap l_g by a conduction material.

By placing a coil in this gap the necessary forces needed will be produced when a current flows through the coil. This happens without making contact. The choice of materials used in voice coil actuator design is dictated by factors such as required system performance, operating environment, manufacturing considerations, and cost. In many cases steel is used as a conductive material, because it is easy to get and can be easily worked with. It also has and adequate magnetic permeability.

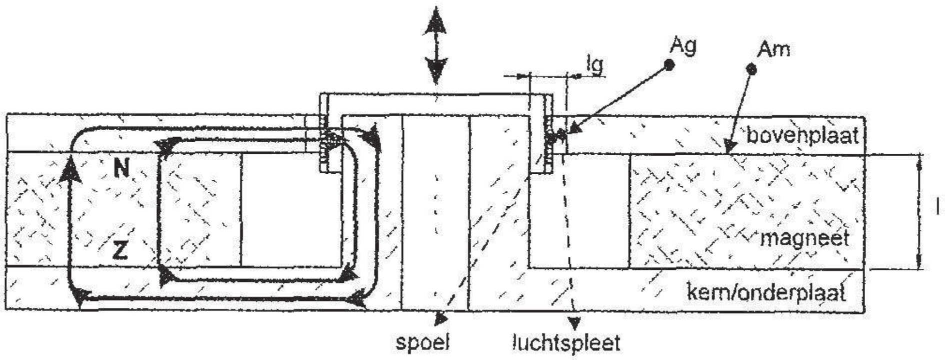


Figure 5.1: Voice coil actuator

The stroke may be specified as the total displacement from one end of travel to the other end, or as a plus/minus (±) displacement from mid-stroke reference. Typical voice coil strokes range from microns to ± 1-4 inch: however, longer strokes are possible. But this increases the mass and volume of the voice coil. This condition results from the added magnet materials needed in long stroke applications, as well as the additional back-iron needed to carry the flux of the extra magnets. Force and stroke usually have an inverse relationship; high force/short-stroke, or low-force/long-stroke.

The electromechanical conversion mechanism of a voice coil actuator is governed by the Lorentz Force Principle. This law of physics states that when a current-carrying conductor is placed in a magnetic field, a force will act upon it. The force produced by the actuator is given by equation 5.2.

$$F = k\,B\,L\,I\,N \tag{5.1}$$

A conductor moving through a magnetic field will have a voltage induced across the conductor. The voltage potential that is induced in the conductor is given by equation 5.2

$$E = k\,B\,L\,v\,N \tag{5.2}$$

F is the magnitude of the force;
E is the magnitude of the voltage, dependant on B;
B is the magnetic flux density;
I is the current;
L is the length of the conductor;
N is the total number of conductors with length L;
k is a constant;
v is the speed of the conductor;

The direction of the force generation is a function of the direction of current and magnetic field vectors. Moreover, it is the cross-product of the two vectors. If current flow is reversed, the direction of the force on the conductor will also reverse. If the magnetic field and the conductor length are constant, as they are in a voice coil actuator, then the generated force is directly proportional to the input current [4].

5.3 Pros and cons general VCA

VCA's are typically uncommutated, meaning that the entire coil becomes energized when a voltage is applied. This is a source of inefficiency for voice coils, as waste heat is produced even in the coils that are not contributing significantly to the force produced by the actuator. The major advantages of electromagnetic actuators are:

- Speed
- Smooth and silent operation
- High efficiencies
- Low wear, thus long life
- Ease of implementation
- Excellent shock loading tolerance
- Robustness to overloading

Robustness to overloading means that when, for example, a directly-driven VCA is pushed against the direction of its force, it will simply continue to apply a force proportional to its current, and allow itself to be backdriven if the force exceeds that value. Power input to the actuator in the form of current is then dissipated as heat. This fundamental property of VCAs is a key safety advantage in cases where a force is applied perpendicular to the needle and thus indirectly to the VCA. This force could be the hand of the person being treated, accidently bumping into the needle.

5.4 Voice coil actuator

The moving parts of the speaker must have a low mass so that is why voice coils are usually made with the most light weight wire possible. Because of this, passing too much current through the coil can cause it to overheat. Voice coils wound with flat wire (so-called flat-wound voice coils) are better able to dissipate heat than coils made of round wire. The fields produced by the permanent magnets embedded on the inside diameter of a ferromagnetic cylinder are arranged so that the magnets facing the coil are all of the same polarity. An inner core of ferromagnetic material set along the axial centerline of the coil, joined at one end to the permanent magnet assembly, is used to complete the magnetic circuit. The force generated axially upon the coil when current flows through the coil will produce relative motion between the field assembly and the coil, provided the force is large enough to overcome friction, inertia, and any other forces from loads attached to the coil.

5.4.1 Advantages and disadvantages

The advantages of the moving-coil actuator:

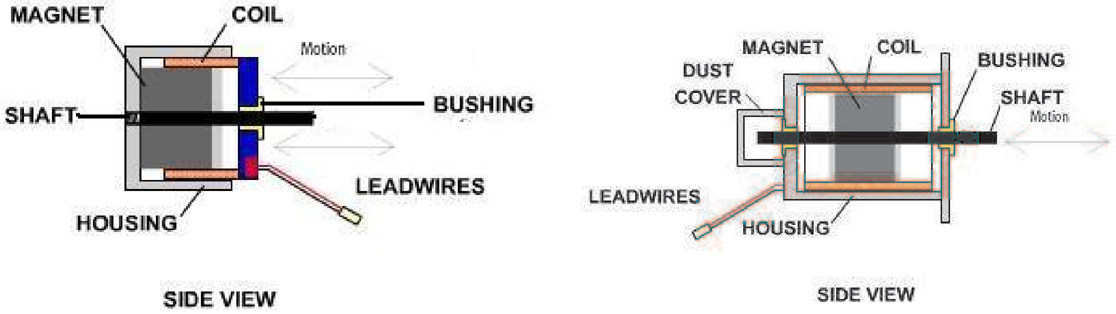
- The force is proportional to the electric current. This is the reason that the behavior of the VCA is predictable and so during the designing proces the desired accuracy can be determined very well.
- The low mass of the moving part, the yoke and the coil, makes high accelerations together with high bandwidths possible.
- Due to the high magnetic flux in combination with a small air gap a high motorconstant is possible.
- Because the VCA is non-commutated and there is little friction it is simple and accurate to control with direct current (DC)
- A high positioning precision is possible with a feedback measuring system. This accuracy is dependant on the precision of the control and the position measuring signal.

The disadvantages of the moving-coil actuator:

- Limited stroke with high efficiency, a longer stroke means more windings outside the magnetic field and hence a lower efficiency.
- When a force has to be delivered at standstill, heat dissipation takes place to keep the coil in its position.

5.5 Moving-Magnet Actuator MMC

A simple view of a moving magnet motor is illustrated in Figure 5.2. The moving magnet motor exists of three basic elements: the magnet, the coils, and the core. In this figure, the magnet moves to the left and to the right while the coils and core remain stationary. The structure has depth w into the paper. The magnet is magnetized with two polarities as illustrated. While a moving-magnet design can result in a slightly greater moving mass, it affords a simpler construction geometry enabling smaller, more streamlined actuators. The function of the coil and core assembly (also known as a stator) is to carry and modulate the flux across the gap where the magnet resides. The two sections of core are connected to complete the magnetic path. The coils are wound and connected so that magnetic flux



(a) Moving-coil

(b) Moving-magnet

Figure 5.2: Two types of voice coil actuators

generated by the current in each coil adds constructively in the gap of the motor. The flux generated by the coils interacts with the flux generated by the magnet causing the magnet to react with a force either left or right depending on the polarity of the coil flux. A simpler way to describe this is to view the core and coil combination as an electromagnet producing a north and south pole as a function of current. When the current is applied, the appropriate poles of the magnet are either attracted or repelled producing the force. The stronger the current is the stronger the resulting force is. The structure implemented will produce a force that is directly proportional to the current in the coils. Maximum force is only limited by the thermal performance of the overall system design [2]

To keep the performance of the motor optimal, the gap between the magnet and core must be very small compared to the thickness of the magnet. Most important to the functionality of the moving magnet actuator is the mechanical suspension. This suspension performs a number of important functions:

- The suspension allows the magnet to move along the desired axial path with minimal use of the motor force.
- The suspension keeps the magnet from crashing against the face of the core. Contact with the core would produce undesirable friction and nonlinear behavior of the motor.
- The suspension is expected to last indefinitely over the normal operating range and life of the motor.
- Friction is expected to be kept at a minimum.
- The high acceleration capability of the motor will be good if the suspension has a low moving mass.

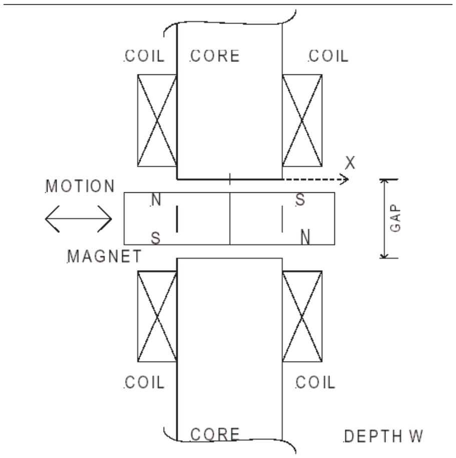


Figure 5.3: Moving-magnet-actuator

5.5.1 Advantages and disadvantages

There are several advantages in having the magnet of a linear motor move relative to a stationary coil set.

- The stationary drive coils are intimately mounted to a structure that can be more effectively heat sunk. This is needed, because then the resistance would not change that much due to heating.
- Since the coils are stationary their mass does not affect the maximum velocity of the motor. As a result a larger coil may be used which enables a highly efficient motor design.
- The coils are stationary, so there are no loose leads.
- Due to the design of the moving magnet, it does not make contact with any of the stationary elements of the motor. Because of this there is no frictional wear.

A major disadvantage is the greater mass that has to be moved. [2]

5.6 Moving-magnet versus Moving-coil

The total construction of actuator and needle has to be as light as possible. Also if the actuator has to be suspended vertically, gravity will cause a this mass to translate into a large force, when the mass is big. This is not pleasant for the actuator, because it has to compensate this force. In Table 5.1 the same model of both actuators are compared. The moving mass of the moving-coil actuator and the moving-magnet actuator translate into

Table 5.1: Moving-coil versus moving-magnet

Actuator type	Movingcoil	Movingmagnet	Unit
Stroke	25.4	25.4	mm
Continuous force	10	8.8	N
Peak force	30	26.4	N
Force constant	3.56	4.62	$N/(watt)^{0.5}$
Outside diameter	38.1	38.1	mm
Housing length	49.0	108.0	mm
Moving mass	7	210	gram
Total mass	56	750	gram
Resistance	7.3	3.5	watt

forces F_z equal to 0.07 N and 2.06 N respectively. So instead of the moving-magnet, the moving-coil actuator will be used for the actuation of the plasma needle.

The acceleration needed for the voice-coil actuator in the x-y position can be determined, through the triangular move as is shown in 5.4.

1. For the acceleration portion of the curve: $V_{max} = D/(2t_1)$
2. For the entire move: $V_{tri} = (1/2D + 1/2D)/(t_1 + t_3) = D/(2t_1)$
3. $V_{max}/V_{tri} = 2$

D is the total distance traveled by the moving coil; t_1 is the acceleration time; t_2 is the run time; t_3 is the deceleration time; t_4 is the dwell time.

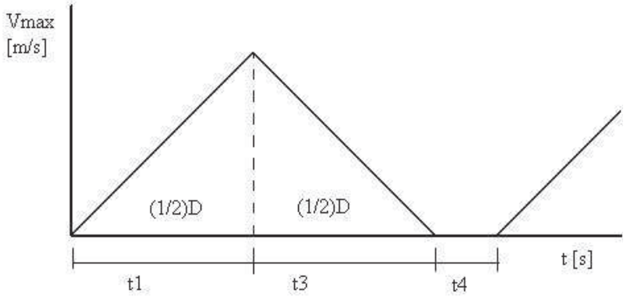


Figure 5.4: Triangular move

Chapter 6

The x-y displacement

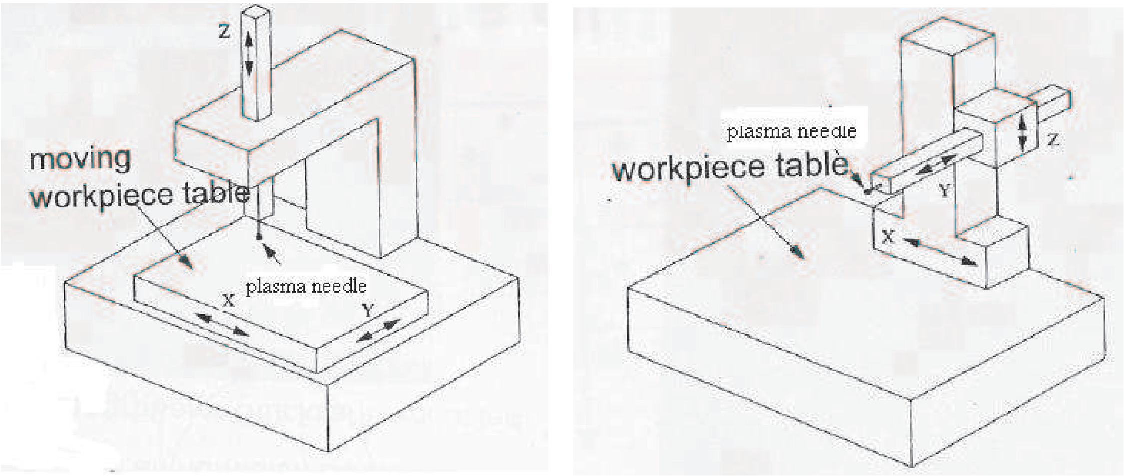
For the needle to be able to move handsfree with an accuracy of 10% an x-y guiding is required. In the four figures below there are four models given. The following conclusions are drawn from these figures:

- In Figure 6.1 model a is a good option when it comes to the array of small compartments containing skin cells. But when e.g a hand has to be treated this model doesn't qualify, because the workpiece table moves in both the the x and the y direction. Therefore it is not suitable for other areas but the compartments.
- Model b is not a good option, because the needle would be positioned horizontally instead of vertically. And because plasma takes the shortest route to the to be treated area, it would also be hard to determine the position of the plasma.
- Both model c and model d are good options for hand as well as compartments.

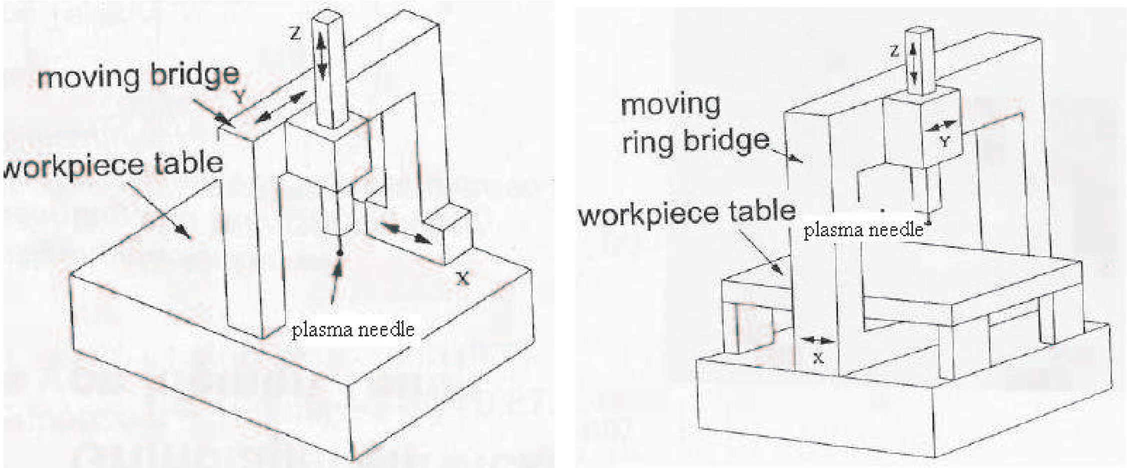
A possible issue is the connection in series of the x, the y and the z movement. This is not preferable, because if there is are errors in the three directions, they will be summated. Thus causing the positioning error to be large. There are many possible sources of error like:

- clearances
- inaccuracy of encoders
- material expansion due to temperature and pressure
- Abbe error
- Bryan error

Errors cause by the actuator will be very small, because an accurate actuator like the voice coil described in chapter 4 is used. So small, in fact, that summation of the three errors will still be less than the required 10%.



(a) Moving workpiece table (b) Moving needle



(c) Moving bridge (d) Moving ring bridge

Figure 6.1: Four possible model for the x and y guidance

Chapter 7

Conclusion

From the previous six chapters conclusions are drawn. These are presented in this chapter.

When it comes to the guidance in the z direction, aerostatic bearings are used. These are radial bearings which are supplied with air instead of the desired helium gas. It turns out that amount of helium gas that was being used by the bearings equals 30.80 l/min. This is far too much, so the conventional gas, air, will be used. The air usage equals 4.57 l/min. The factor that causes this difference in gas usage is the density of the gasses. The density of helium is about 7 times larger than the density of air.

The design for the plasma needle and guidance exists of a hollow cylinder with a hollow wall. The helium supply-tube is connected to a hollow needle which translates inside the hollow cylinder. Through the hollow wall pressurized air is supplied for the bearings.

To allow the hollow needle to translate, an actuator is needed. A moving-coil actuator was found fit for this design, mostly because of its low moving mass. The low moving mass doesn't cause very much reduction of the acceleration and so there is no high power needed.

For the x and y movement a few possibilities are given. Each of them, except for the moving needle model, are usable. Especially the moving bridge and moving ring bridge are useful for both treatment on hands and skin cells in compartments for experimental purposes.

Chapter 8

Further research

The things that still have to be researched more intensively before this design can be manufactured:

- The feedback control for the actuator
- The x-y guiding
- The needed acceleration for the actuator
- The dimensions of the actuator
- The sensors to control the positioning of the needle

Appendix A

List of symbols

Table A.1: List of symbols: aerostatic bearings

h	gap
ρ	density
T	temperature
ps	supply pressure
p0	supply pressure
pa	atmospheric pressure
pd	gap pressure
hk	pocket hight
L	length bearingfoot
D	diameter needle
d	diameter restrictor
Stot	total stiffness
Mtot	total gas usage
n	number of nozzles per radial bearing
N	number of bearingfeet per radial bearing

Table A.2: List of symbols: voice coil actuator

F	magnitude of the force
E	magnitude of the voltage
B	magnetic flux density
N	total number of conductors
D	total distance traveled by moving coil
n	number of coils of wire
d	average diameter of coil
I	electric current
l	conductor length
k	constant
v	conductor speed
t_1	acceleration time
t_2	run time
t_3	deceleration time
t_4	dwell time

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