UNIVERSITY OF TWENTE.

Faculty of Technische Natuurwetenschappen

Influence of dynamic flow field on untethered robots controlled by a magnetic field

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B.Sc. Thesis
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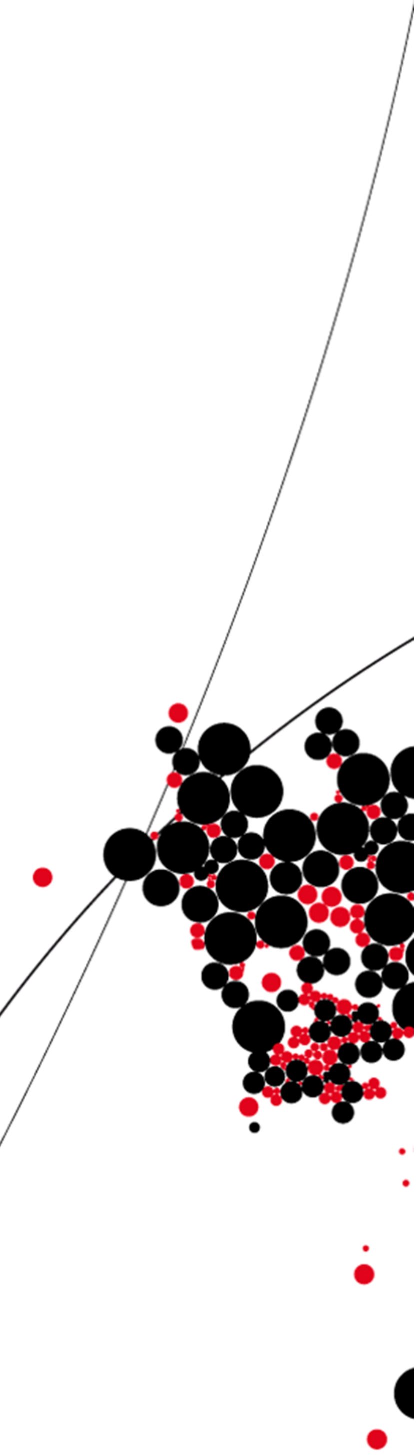

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1 Abstract

This thesis is about the influence of a dynamic flow field on microbots controlled by a static magnetic field. First of all it is important to know what the relevance of the research is. In the current situation anticoagulants are used to help solve thrombosis. This has a couple of unwanted side effects, such as jaundice and excessive bleeding. To solve thrombosis another way there are researches like these. In this research magnetic actuation controlled microbots are used. Therefore the magnetic actuation is explained and modelled to get a theoretical answer. After that, there are experiments done to test the theory and look into the physical limits of the used technology. From these experiments we can draw the conclusion that the microbots which are controlled by a static magnetic field can move through a low dynamic flow field when the actuation frequency ranges between 1 and 10Hz. All the experiments are done in water with the flow rates 0, 5, 10, 15 and $20\mathrm{mL\,min^{-1}}$. To get a better view of the limits of this technology further research need to be done. There is a need to look at more actuation frequencies to determine the step out frequency and it is useful to look at higher flow rates and different microbots.

Contents

2 Introduction

Venous thrombosis remains a significant health concern affecting a considerable number of individuals, with an estimated 10 million cases reported annually. The current approach to managing this condition involves the use of anticoagulants [1], which aim to prevent the existing clot from enlarging and migrating to the lungs, while also reducing the likelihood of new clots forming and diminishing the chances of recurrence. However, the administration of anticoagulants comes with inherent risks, primarily related to their blood-thinning properties. These medications can lead to excessive bleeding as they prolong the blood clotting process.[2] Consequently, patients on certain anticoagulants often require regular hospital visits for risk assessments to identify if they are prone to severe bleeding complications. Moreover, anticoagulants are associated with a range of other potential side effects, varying from mild issues like constipation to more severe conditions such as jaundice.

Given the drawbacks of using anticoagulants, exploring alternative solutions for the treatment of blood clots has become imperative [3]. One promising avenue involves investigating the potential of microbots within the body. These tiny robotic devices could navigate through the bloodstream and physically interact with blood clots, breaking them into smaller, more manageable pieces. By fragmenting the clots, the microbots facilitate their dissolution, offering a novel and potentially safer approach to address thrombosis.

In this context, the present research seeks to delve into the realm of microbot technology and its application in the management of venous thrombosis. By harnessing the capabilities of these minuscule yet powerful machines, the aim is to develop a minimally invasive and effective treatment modality that can target and disintegrate blood clots, subsequently aiding in their dissolution. This cutting-edge exploration holds the promise of revolutionizing thrombosis treatment, presenting a hopeful prospect for millions of individuals impacted by this medical condition.

This microbot technology can be applied by using magnetic actuation to control the untethered robot. Magnetic actuation is especially useful in dynamic Newtonian-Viscoelastic flow fields with a wide range of Reynolds number [4]. It is also harmless to cells and tissues so it has great potential for a lot of applications in the medical world. The properties of the fluids can vary in time and space and it is possible this has an influence on the path of the robot. To make the technology work in these varying environments it is important to look at the input-output boundedness of the robot controlled by magentic actuation [5]. There are different ways to make the magnetic actuation technology viable to use. The technology can be used with an electromagnetic and a permanent-magnet system. Electromagnetic systems make use of a configuration of electromagnetic coils that are powered independently. Permanent-magnet systems mage use of rotating permanent magnets. Permanent-magnet based systems make for an easier scale up for clinical application, because of the electromagnetic coils which are hard to scale up. Therefore looking at a single rotating permanent magnet is more useful. The applications in the medical field can go much further this way [6].

As the investigation unfolds, it is expected that valuable insights will be gained, paving the way for advancements in medical science. By scrutinizing the potential of microbots in combating thrombosis, this research endeavors to contribute significantly to the field of healthcare, offering an innovative and transformative solution to a widespread health issue. Ultimately, the findings and discoveries resulting from this study could revolutionize the way we approach and treat venous thrombosis, bringing us one step closer to a safer and more efficient treatment paradigm.

3 Magnetic-Based Wireless Actuation of Untethered robots

3.1 Magnetic actuation

For this research magnetic actuation is used. Magnetic actuation is about controlling the motion of an object or system. It uses magnetic forces and magnetic materials to generate force and torque [7]. The method used in this research relies on two permanent magnet, of which one is in the helical screw. The other magnet is attached to the KUKA arm. By placing the magnets on a fixed distance to each other and headed in the same direction, you can manipulate the rotation of the magnet on the KUKA arm and the magnet in the screw will spin accordingly [8]. To get the right distance between the magnets so they are bound [5], but not attracting or falling, it is important to look at the magnetic torque. Given in equation 1

$$\tau = \mu B \sin\theta, \tag{1}$$

where τ is the magnetic torque, μ is the magnetic moment, B is the flux density and θ is the angle between the magnetic moment vector and the magnetic field vector, as shown in figure 1. The distance between the centers of the two magnets follows the inverse square law. This relationship can be expressed as:

$$\tau \propto \frac{1}{r^2}, \tag{2}$$

where r is the distance between the centre of the permanent magnet and the centre of the helical screw. Using these equations an optimal distance can be derived to perform the experiments. In figure 1 below a schematic overview about magnetic actuation.

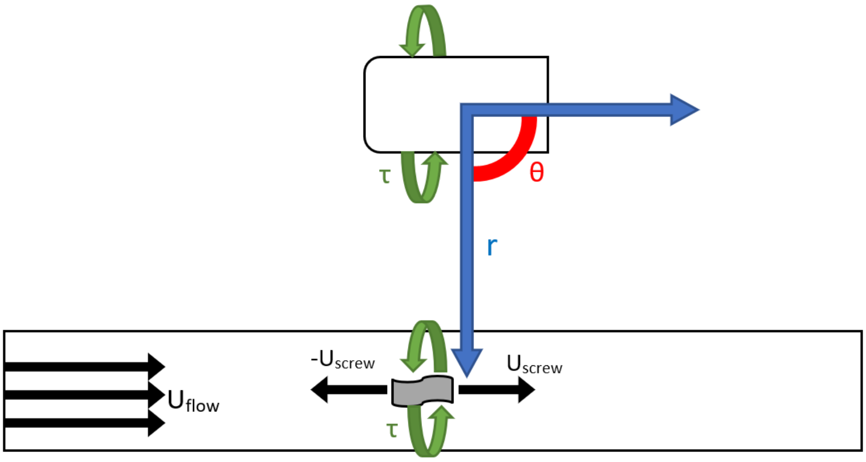


Figure 1: Schematic overview of magnetic actuation with the direction of the flow field

3.2 Hydro fluid dynamics

The fluid used for this research is water, because of its Newtonian properties [9]. The strain rate is linearly correlated to its viscous stress. This means the viscosity is constant. A Newtonian fluid can be described by the following equation.

$$\sigma = \mu \frac{du}{dy}, \tag{3}$$

where σ is the shear stress of the fluid, μ is the shear viscosity of the fluid and $\frac{du}{dy}$ is the derivative of the velocity parallel to the direction of shear.Using a Newtonian fluid makes the experiments a lot simpler and the results more clear, because of the linear behavior. When the experiments would be done in blood it is important to look at the fluid's viscoelastic properties. These properties are due to the composition of blood. The viscoelasticity are mostly caused by the microstructures produced by the red blood cells.

3.3 Flow field dynamics

The robot is build out of a magnet surrounded by a polymer. It is shaped as a helical screw. The shape makes it so the robot can propel through the fluid. The magnet in the robot is actuated by a permanent magnet-based robotic system. Permanent magnets have a fixed magnetic field that can exert forces on other magnetic materials or objects with magnetic properties[10]. By strategically placing permanent magnets and arranging their orientation, attractive or repulsive forces can be generated, leading to motion or manipulation of objects. In this case the object with magnetic properties is the helical robot. By turning the permanent magnet of the robotic system with a certain frequency, a magnetic torque is generated. This will make the helical robot turn with an angular velocity ω. It will also give the helical robot a linear velocity. Which is shown in equation 4.

$$U = 2A\omega\epsilon^2 \sum_{q\geq 1} \frac{(1+\beta q^2 De^2)\ |\hat{f}_q|}{1+q^2De^2} J_q \tag{4}$$

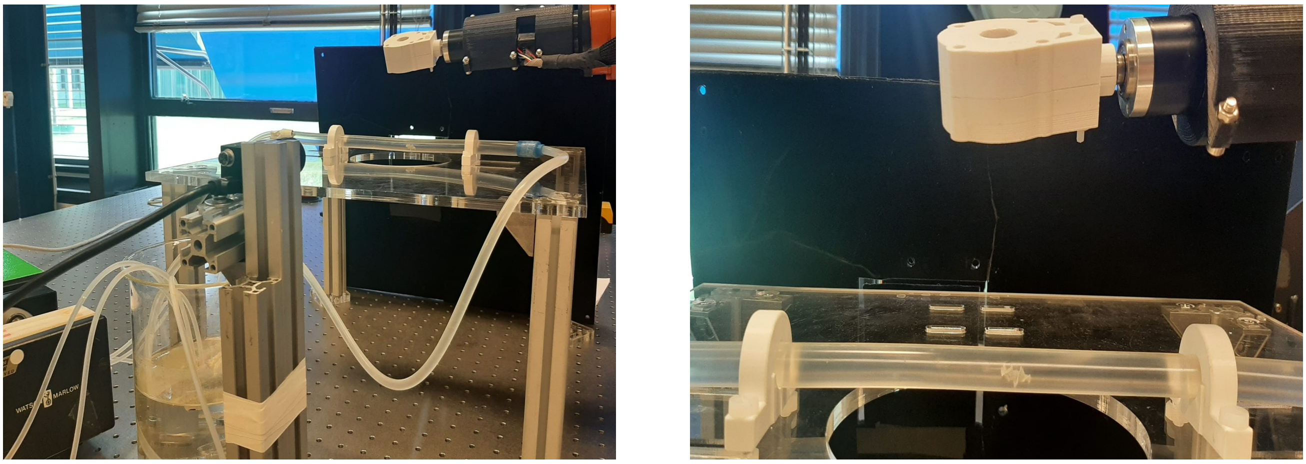
In this equation A is the radius of the screw. β is the ratio of solvent viscosity to total viscosity. q is the vector of the joint space coordinates. $\hat{f}_q$ is the Fourier analysis of the periodic function $f(N\theta)$ and J_q is based on the Bessel function. De is the Deborah number. This can be calculated by

$$De = \lambda\omega, \tag{5}$$

where λ is the fluid relaxation timescale [10]. Blood in the body has different flow rates. These vary from $1.2\ \mathrm{mL\,min^{-1}}$ in the fingertips to $5\ \mathrm{L\,min^{-1}}$ in the aorta [11]. In the renal To achieve this with the peristaltic pump used, it is needed to recalculate the speed of the robot. So we can modify the equation of the speed given by equation 4 with the speed of the flow. We obtain the next equation.

$$U = 2A\omega\epsilon^2 \sum_{q\geq 1} \frac{(1+\beta q^2 De^2)\ |\hat{f}_q|}{1+q^2De^2} J_q + U_{flow} \tag{6}$$

The modified equation can give us a expected frequency response with induced flow. This gives a perception of the influence of the flow on the speed of the robot.


(a) The full setup used for the experiments

(b) closeup tube and KUKA arm

Figure 2: The setup for the experiments

4 Methodology

4.1 Experimental setup helical device in controlled system

The setup used for this research is composed of different devices and tubes which will be discussed separately. The full setup used can be seen in figure 2a. A closeup of the magnet and the helical screw used can be seen in figure 2b. It is used to perform static experiments to get the frequency response of a helical device in a controlled environment.

4.1.1 Setup devices

4.1.1.1 Flow inducing system

The pump used for this setup is a peristaltic pump form Hewlett and Packard. It can pump up to 20 mL min^{-1}. So for this research the flow rates of 0 mL min^{-1}, 5 mL min^{-1}, 10 mL min^{-1}, 15 mL min^{-1} and 20 mL min^{-1} are used.

4.1.1.2 Wireless manipulation system

This setup made use of a KUKA KR 10 R1100-2. This was used to make the actuating magnet spin around the z-axis. The gap between the actuating magnet and the helical screw used was 0.1 m. The speed used when doing the experiments with the dynamic arm movement was with the speed of the arm on 5% and the speed setting in RoboDK, the program used to control the robot automatic, was set to 200 mm s^{-1} to achieve a speed of 10 mm s^{-1}.

4.1.1.3 Helical screw

The helical screw used, was made by another member of the research department. It was designed in such a way, when the screw spins around its axis, it gets a forwards or backwards paddling movement, because of the small magnet within the helical screw. This way when the actuating magnet spins faster, the helical screw will spin faster and it will move faster through the fluid. As seen in previous research it will have a step out frequency, where if the actuating magnet has a spinning frequency which is to high, the helical screw will not move forwards anymore.

4.1.2 Tubes used in experimental setup

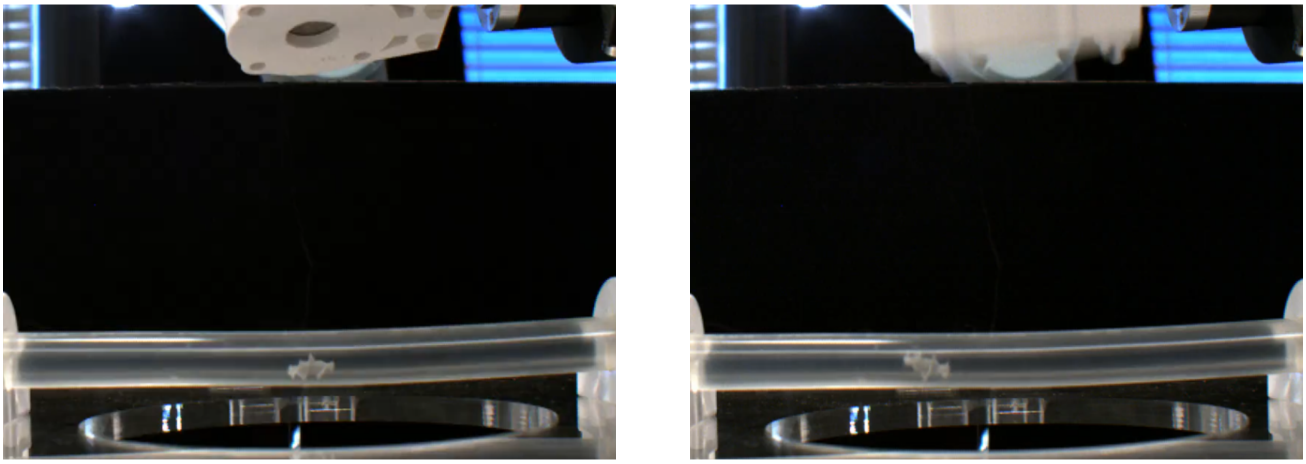
The setup used for the experiments is build out of multiple components. For the tube with the screw, a with an inner diameter of 9.54 mm and an outer diameter of 11.96 mm is used. For the capillary tubes to work with the pump, three tubes with an inner diameter of 3 mm and an outer diameter of 4 mm are used. the last tube, which is from the tube with the screw and to the reservoir, has an inner diameter of 5 mm and an outer diameter of 7 mm.

4.2 Measurements

All the measurements were done with the above described setup. First all of the measurements with the static KUKA arm are done. For these experiments, the helical screw is placed in the middle of the tube, beneath the middle of the actuating magnet, see 3a in the figure below. Then the magnet will be turned on and is spinning in the direction moving against the flow field, so the helical screw will move against the flow, see 3b. After a couple of seconds the actuating magnet will switch to turning the other way, the helical screw will also switch to turning the other way and starts moving with the flow back to the middle, see 3c. It moves beyond the middle to the right most point, see 3d. This is still with the flow. After this the magnet switches the spinning direction again and the helical screw moves back to the middle, see 3e. These switches are both done twice and then the actuating magnet is stopped. A camera captured these movements and the video is analysed. This measurement is repeated five times for each frequency. For the dynamic measurements the procedure is almost the same, except the measurements start on one side of the tube and the KUKA arm will move to the other side of the tube, while the actuating magnet is turning. When the KUKA arm starts moving back to the initial position the actuating magnet switches to spinning in the other direction. This movement is also done twice and the KUKA arm moves back to the initial position. These measurements are also done five times per frequency.

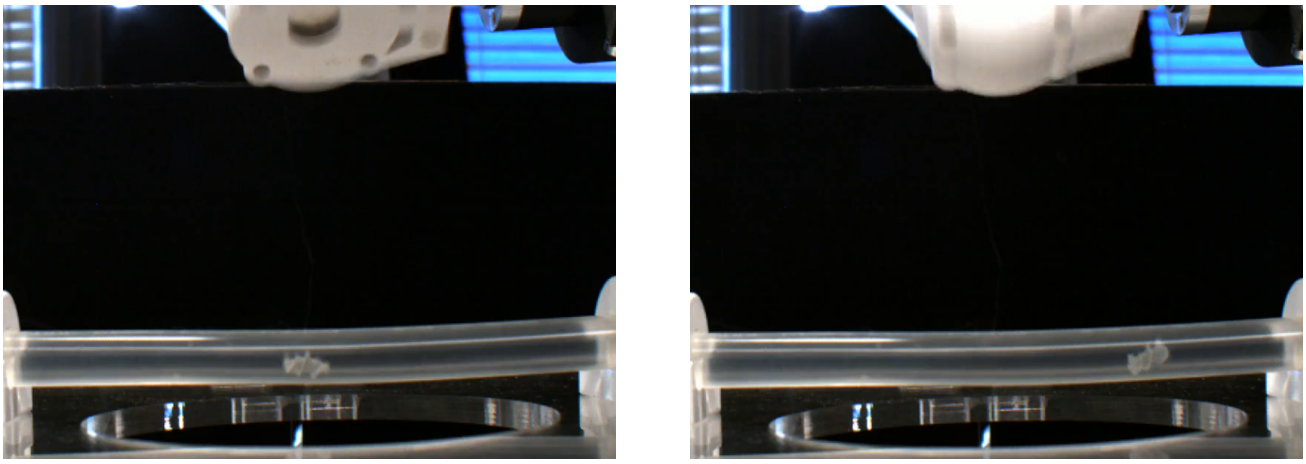
4.3 Processing

To process the measurements, the videos made of the moving screw were run through tracker software to determine the location of the screw. With the location and the time the screw travelled, the velocity was determined. This was set out in a graph which showed the frequency response of the screw at different frequencies at certain flow rates.



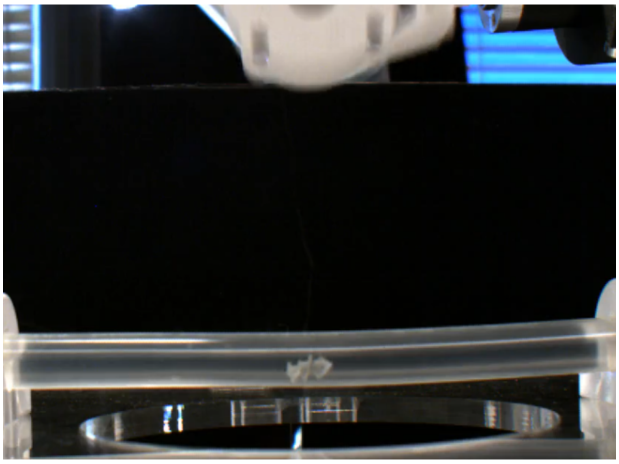
(a) Starting point of the helical screw

(b) Movement against the flow to left most position



(c) Movement with the flow back to the middle

(d) Movement with the flow to right most position

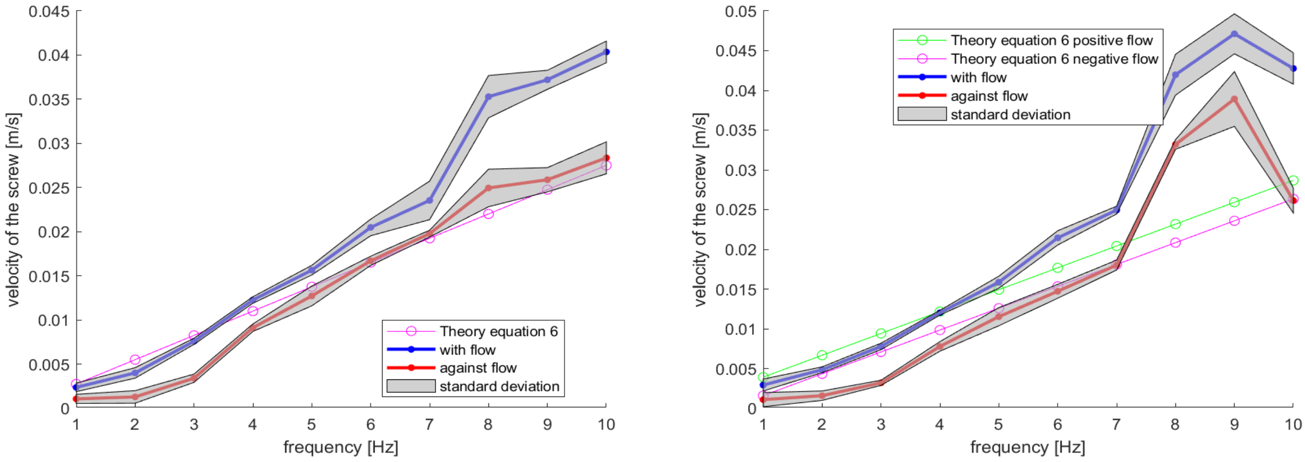


(e) Movement against the flow back to the middle

Figure 3: Time lapse of the experiments for clarity

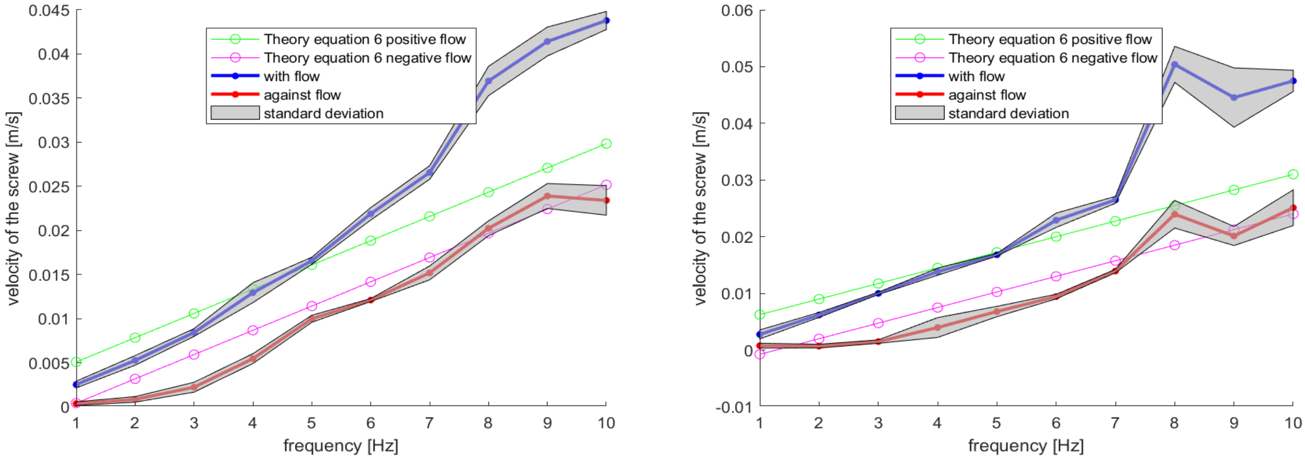
5 Results

In the graphs shown below are the results of the experiments.



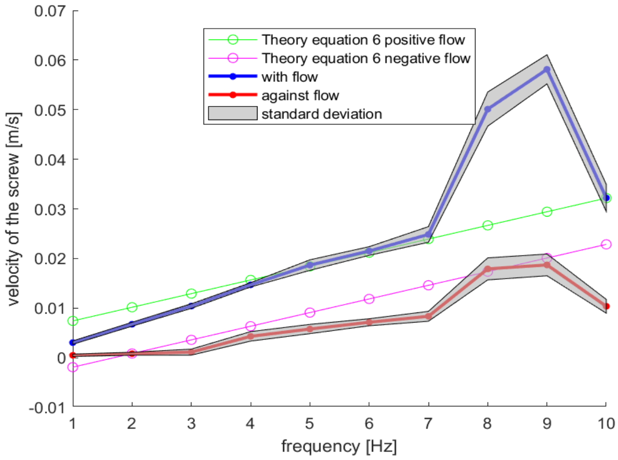
(a) Frequency response 0ml/min static arm

(b) Frequency response 5ml/min static arm



(c) Frequency response 10ml/min static arm

(d) Frequency response 15ml/min static arm



(e) Frequency response 20ml/min static arm

Figure 4: Graphs frequency response at different flow fields

In figure 4a are the experiments shown which were done in an environment without flow. Where the KUKA arm was at a static point, while the helical screw made a rocking motion. There is a difference in frequency response visible between moving with flow and moving against flow. Although there is no flow the experiments are classified as such. Both do not follow the expected value line very well. The measurements with the flow go op in frequency response way faster than expected value. The measurements against the flow are a bit up and under the expected values. At 2 and 3 Hz the measurements against the flow are way under the expected values. At the higher frequencies this is no longer the case. The measurements of with the flow start off looking like the expected values, but at the higher frequencies there is a larger difference visible. At bigger differences in frequency response also a higher standard deviation is seen.

In figure figure 4b the experiments are done with a flow of 5 $\mathrm{mL\,min^{-1}}$. The helical screw makes a rocking motion like in the experiments done without flow. This time there are two lines for the expected flow. One line is the expected values with the flow and the other is expected values against the flow. The measurements for the movement against the flow are also in these experiments a bit up and under the corresponding expected values line. At 5, 6 and 7 Hz the measurements against the flow are in line with the expected values. At 8 and 9 Hz the measurements are a lot higher than the expected frequency response, but at 10 Hz the measurements look again in line with the expected value. For the measurements with the flow. At the lower frequencies the frequency responses are close to the expected values. Form 6 Hz the measurements end up having a lot higher frequency response than expected.

In figure 4c the experiments are done with a flow of 10 $\mathrm{mL\,min^{-1}}$. The helical screw makes a rocking motion like in the experiments done without flow. Once again one line is the expected values with the flow and the other is expected values against the flow. For the measurements for the frequency response against the flow, the measurements are lower than the expected values for most of the frequencies, but it still follows a similar upwards line. The frequency response starts out a bit lower. At 8 Hz the values are almost the same and at 9 and 10 Hz the values are close to the boundaries of the standard deviation. For the measurements with the flow. The frequency response is a bit up and under. For the frequencies from 1 to 4 Hz the values are a bit lower than the expected values. From 6 Hz on the values of the measurements are a lot higher than the expected values.

In figure 4d the experiments are done with a flow of 15 $\mathrm{mL\,min^{-1}}$. The helical screw makes a rocking motion like in the experiments done without flow. Once again one line is the expected values with the flow and the other is expected values against the flow. For the measurements against the flow. The measurements follow the line of the expected values reasonably well. The measurement values are a bit lower between 2 and 7 Hz and are a bit higher at 8 Hz. At 9 and 10 Hz the values are very close to the expected values. The measurements with the flow are at the frequencies between 1 and 7 Hz very much like the expected values. At 8, 9 and 10 Hz the measurement values are a lot higher than the expected values.

In figure 4e the experiments are done with a flow of 20 $\mathrm{mL\,min^{-1}}$. The helical screw makes a rocking motion like in the experiments done without flow. Once again one line is the expected values with the flow and the other is expected values against the flow. For the measurements against the flow. The frequency response of most of the measurements are a bit lower than the expected values, but look still close to the expected values. at 8 and 9 Hz the values are very close to the expected values. At 10 Hz the measurement values are lower than at 9 Hz and are quite a bit lower than the expected value. For the measurements with the flow. Most of the frequency responses are close to the expected values. At 8 and 9 Hz the frequency responses are a lot higher than expected. At 10 Hz on the other hand the measurement values are very much in line with the expected value.

6 Conclusion

From the graphs there are a couple of possible conclusions. There is a visible difference between the frequency response of the different flow fields, this yields a dependence on the flow rate. This is uphold by the theory where you add up the speed of the flow field to the movement speed of the helical screw. This is true for the movement with flow and the movement against flow. There is a visible drop of the frequency response at the higher flow rates this could mean the coupling between the to magnets is worse, which means the step out frequency is reached. It could also mean the step out frequency is near. Therefore more experiments are required. Overall the results for the movement against the flow are more in line with the theory then the movement with the flow.

7 Discussion

The graphs also showed some interesting results. In graph 4a it is visible the frequency response is different between movement with flow and against flow, although there is no induced flow. This could be because of the rocking motion where the robot started by moving against the flow or because of the properties of the robot, and the placement of the magnet inside of the screw. It could also be an inaccuracy in the tracker software and the script used to make the graphs. Also the frequencies where the drops are, especially at graph 4e can be declared by two things. The first one is the step out frequency is reached or second by looking at the videos. The robot picks up a lot of speed and moves out of the magnetic field and then stops till the magnet at the KUKA arm changes the direction of the rotation. This could be solved by writing a specific program for testing at higher flow fields by making the time of movement with flow shorter in comparison with movement against flow. Also the results for movement with and against the flow are very different in comparison with the theory. The movement against the flow follows the theory more then the movement with the flow does. This can be a fault in the script form my side. It can also be inaccurate measurements or another step in the process that could be improved, such as a stricter protocol for measurements or a more accurate measurement of the flow. To make sure the step out frequency is reached there need to be done more experiments, this could be nice for more experiments in future research.

There are a couple aspects this research did not look at much, which also can be done in future research. These experiments are done in water so it is important to do the same experiments in blood as well because of the different properties blood has. Furthermore it would be useful to conduct the experiments at a higher flow field, because the flow in the body can go up to $5\mathrm{L\,min^{-1}}$ which is obviously a lot higher than $20\mathrm{mL\,min^{-1}}$. It can also be useful to do the experiments with different sizes of helical screws and see of it makes a difference. Also it is a possibility to look at a dynamic arm movement to see if that makes a difference in the frequency response, because the setup of these experiments, the helical screw was in a rocking motion underneath the magnet, the screw did not make much distance and when travelling forward and backward there were small distance differences, which changes the frequency response.

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