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Theme

The modeling and the control of an insulin-pump

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Dedication

I want to dedicate my humble effort to the most precious people I know:
To my parents and siblings first, to my dear supervisors, and to those who have accompanied me through the toughest moments of this long educational journey, always supporting and cheering me up. May they find here the testimony of my deepest gratitude and my infinite love for them.
And to all my close family members for their support throughout my university studies.
And especially to my cherished the bitter and the sweet times.

Chaimaa

الملخص

في الوقت الحالي، تهدف الكثير من الدراسات الى تطوير المعدات الطبية و ذلك بهدف تسهيل علاج مختلف الامراض، من بين هذه الامراض مرض السكري المزمن الذي أتعب علاجه الكثير من المرضى بسبب الحقن المستمر للأنسلين خلال النهار، حيث يعمل هذا الأخير على تعديل مستوى السكر أو بالأصح الغلوكوز في الدم، حيث تم تحديث هذه الطرق التقليدية بأساليب سهلة و مريحة للمرضى، من بين هته التقنيات مضخة الأنسلين الأتوماتيكية التي تم تناولها في هذا العمل.
تهدف هذه المذكرة إلى استكشاف آليات التحكم والديناميكيات التشغيلية لمضخات الأنسولين، تُعتبر مضخات الأنسولين أجهزة حيوية لعلاج مرض السكري، حيث توفر ضخًا مستمرًا للأنسولين تحت الجلد للحفاظ على مستويات الجلوكوز المثلى لدى المرضى. تقدم الدراسة نظرة شاملة على مكونات مضخات الأنسولين، بما في ذلك محرك التيار المستمر، مخفض السرعة، آلية اللولب والجوزة، ومجموعة المكبس والاسطوانة، ونمذجتها الرياضية. بهدف مراقبة وضبط تركيز الجلوكوز في الدم. تُظهر التكامل الناجح لهذه الآليات التحكمية إمكانيات تحسين أداء مضخات الأنسولين، مما يساهم في تحقيق نتائج أفضل للمرضى.

الكلمات الدالة : مرض السكري ، الأنسلين ، الغلوكوز ، مضخة الأنسلين ، التحكم الآلي ، المحاكاة

Résumé

Actuellement, de nombreuses études visent à développer des équipements médicaux afin de faciliter le traitement de diverses maladies. Parmi ces maladies, le diabète chronique est particulièrement lourd pour les patients en raison des injections continues d'insuline requises tout au long de la journée pour réguler les niveaux de sucre dans le sang, ou plus précisément, les niveaux de glucose. Les méthodes traditionnelles ont été mises à jour avec des techniques plus faciles et plus confortables pour les patients, dont l'une est la pompe à insuline automatique abordée dans ce travail.

Ce mémoire vise à explorer les mécanismes de contrôle et les dynamiques opérationnelles des pompes à insuline. Les pompes à insuline sont des dispositifs vitaux pour le traitement du diabète, fournissant une infusion continue d'insuline sous-cutanée pour maintenir des niveaux de glucose optimaux chez les patients. L'étude offre une vue d'ensemble complète des composants des pompes à insuline, y compris le moteur à courant continu, le réducteur de vitesse, le mécanisme vis-écrou, et l'ensemble piston-cylindre, ainsi que leur modélisation mathématique. L'objectif est de surveiller et de réguler la concentration de glucose dans le sang. L'intégration réussie de ces mécanismes de contrôle démontre le potentiel d'amélioration des performances des pompes à insuline, contribuant à de meilleurs résultats pour les patients.

Mots clés : Diabète, insuline, glucose, pompe à insuline, contrôle automatique, PID, simulation.

Abstarct

Currently, many studies aim to develop medical equipment to facilitate the treatment of various diseases. Among these diseases, chronic diabetes is particularly burdensome for patients due to the continuous insulin injections required throughout the day to regulate blood sugar, or more precisely, glucose levels in the blood. Traditional methods have been updated with easier and more comfortable techniques for patients, one of which is the automatic insulin pump addressed in this work.

This master thesis aims to explore the control mechanisms and operational dynamics of insulin pumps. Insulin pumps are vital devices for the treatment of diabetes, providing continuous subcutaneous insulin infusion to maintain optimal glucose levels in patients. The study offers a comprehensive overview of the components of insulin pumps, including the DC motor, speed reducer, screw and nut mechanism, and the piston-cylinder assembly, along with their mathematical modeling. The goal is to monitor and regulate blood glucose concentration. The successful integration of these control mechanisms demonstrates the potential to improve the performance of insulin pumps, contributing to better patient outcomes..

Keywords : Diabetes, insulin, glucose, insulin pump, automatic control, PID, simulation.

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General Introduction

General introduction

In the annals of human history, few epochs rival the transformative impact of the technological and scientific revolutions that have reshaped our world. From the advent of electricity to the age of information technology, each leap forward has propelled humanity into new frontiers of knowledge and capability.

Central to this narrative of progress is the field of medicine, where innovations and discoveries have not only extended the bounds of human longevity but have also provided relief and hope to millions battling with ailments once deemed insurmountable. Among the myriad conditions that have challenged medical science, few have proven as pervasive and pernicious as diabetes.

Diabetes, a metabolic disorder characterized by elevated blood sugar levels, has emerged as a global health crisis, affecting individuals of all ages and demographics. Its prevalence has surged in tandem with the rise of sedentary lifestyles, poor dietary habits, and an aging population, making it a formidable adversary for healthcare systems worldwide.

Yet, despite decades of research and investment, a cure for diabetes remains elusive. Instead, the management of this chronic condition relies on a complex interplay of lifestyle modifications, pharmacotherapy, and monitoring to mitigate its debilitating effects. From insulin injections to oral medications, the armamentarium of treatments has expanded significantly, offering patients a semblance of control over their condition.

Amidst this landscape of ongoing challenges and incremental progress, one innovation stands out as a beacon of hope: the insulin pump. A marvel of modern engineering, the insulin pump represents a paradigm shift in diabetes care, offering patients a more precise and convenient method of administering insulin while minimizing the fluctuations in blood sugar levels that characterize traditional injection-based therapies.

In the following dissertation, we embark on a journey to explore the intricacies of diabetes and the revolutionary role played by insulin pumps in its management. Through a comprehensive examination of the disease's etiology, pathophysiology, and treatment modalities, we seek to unravel the complexities of diabetes care and shed light on the trans formative potential of innovative technologies.

Our investigation will span three distinct chapters, each delving deeper into the multi-faceted aspects of our chosen topic. In the initial chapter, we lay the groundwork by

providing a comprehensive overview of diabetes, encompassing its epidemiology, classification, etiology, and clinical manifestations. We will also explore the various treatment modalities available, from conventional insulin therapies to emerging technologies such as continuous glucose monitoring and closed-loop systems.

Building upon this foundation, the second chapter will delve into the mechanics of insulin pump technology, dissecting its constituent components and elucidating the principles that underpin its operation. Through a synthesis of mathematical models, engineering principles, and physiological insights, we aim to construct a comprehensive framework for understanding the intricacies of insulin pump therapy.

Finally, in the third chapter, we will leverage the power of computational simulation to simulate the behavior of insulin pump components using MATLAB/SIMULINK. By harnessing the capabilities of this sophisticated software platform, we will explore the dynamic interactions between pump components and evaluate the open-loop and the closed-loop performance under various scenarios, depending on the BERGMAN model mainly which is provided a long time ago in medical applications, arriving to the pump regulation with *PID* controller.

In undertaking these endeavors, we hope to not only deepen our understanding of diabetes and insulin pump therapy but also contribute to the ongoing dialogue surrounding the future of diabetes care. Through rigorous inquiry and empirical analysis, we aspire to advance the frontiers of knowledge and pave the way for more effective and patient-centric approaches to managing this chronic condition.

Chapter 1
General

1 Introduction

Diabetes mellitus poses significant challenges to healthcare worldwide, characterized by elevated blood glucose levels resulting from insulin dysfunction. This chapter delves into the intricacies of diabetes, encompassing its types, diagnostic criteria, and treatment modalities, with a particular emphasis on the revolutionary role of insulin pumps in managing this condition.

2 Diabetes

Diabetes is a disease that occurs when your blood glucose, also called blood sugar, is too high. Glucose is your body's main source of energy. Your body can make it, but it also comes from the food you eat.
Insulin is a hormone made by the pancreas that helps glucose get into your cells to be used for energy. If you have diabetes, your body doesn't make enough or any insulin, or doesn't use insulin properly. Glucose then stays in your blood and doesn't reach your cells.
Diabetes raises the risk of damaged eyes, kidneys, nerves, and heart. Diabetes is also linked to some types of cancer. Taking steps to prevent or manage diabetes may lower your risk of developing many health problems.[1]

3 Different types of diabetes

The most common types of diabetes are type 1, type 2, and gestational diabetes.

3.1 Diabetes type 1

Type 1 diabetes, once known as juvenile diabetes or insulin-dependent diabetes, is a chronic disease. In this condition, the pancreas makes little or no insulin. Insulin is a hormone the body uses to allow sugar (glucose) to enter cells to produce energy.

Different factors, such as genetics and some viruses, may cause type 1 diabetes. Although type 1 diabetes usually appears during childhood or adolescence, it can develop in adults.

Even after a lot of research, type 1 diabetes has no cure. Treatment is directed toward managing the amount of sugar in the blood using insulin, diet and lifestyle to prevent

complications.[2]

3.2 Diabetes type 2

Type 2 diabetes is a condition that happens because of a problem in the way the body regulates and uses sugar as a fuel. That sugar also is called glucose. This long-term condition results in too much sugar circulating in the blood. Eventually, high blood sugar levels can lead to disorders of the circulatory, nervous and immune systems.
In type 2 diabetes, there are primarily two problems. The pancreas does not produce enough insulin, and cells respond poorly to insulin and take in less sugar.
Type 2 diabetes used to be known as adult-onset diabetes, but both type 1 and type 2 diabetes can begin during childhood and adulthood. Type 2 is more common in older adults. But the increase in the number of children with obesity has led to more cases of type 2 diabetes in younger people.
There's no cure for type 2 diabetes. Losing weight, eating well and exercising can help manage the disease. If diet and exercise aren't enough to control blood sugar, diabetes medications or insulin therapy may be recommended.[2]

3.3 Gestational diabetes

Gestational diabetes is a type of diabetes that develops during pregnancy. Most of the time, this type of diabetes goes away after the baby is born. However, if you've had gestational diabetes, you have a higher chance of developing type 2 diabetes later in life. Sometimes diabetes diagnosed during pregnancy is type 2 diabetes. [2]

4 Diagnostic

The diagnostic criteria for diabetes mellitus are typically established by reputable health organizations such as the American Diabetes Association (ADA) and the World Health Organization (WHO). Here are the diagnostic criteria for diabetes according to the ADA:

- A1C Test: This test measures your average blood sugar level over the past 2-3 months. If your A1C level is 6.5 *PER CENT* or higher on two separate occasions, it indicates diabetes.

- Fasting Plasma Glucose (FPG) Test: This test measures your blood sugar level after an overnight fast (no food or drink except water for at least 8 hours). A fasting blood sugar level of 126 milligrams per deciliter *(mg/dL)* or higher on two separate tests indicates diabetes.

- Oral Glucose Tolerance Test (OGTT): This test involves fasting overnight and then drinking a sugary solution. Blood sugar levels are measured before drinking the solution and again 2 hours after. A blood sugar level of 200 mg/dL or higher 2 hours after drinking the solution indicates diabetes.[3]

5 Treatment

Depending on what type of diabetes you have, blood sugar monitoring, insulin and oral drugs may be part of your treatment. Eating a healthy diet, staying at a healthy weight and getting regular physical activity also are important parts of managing diabetes.

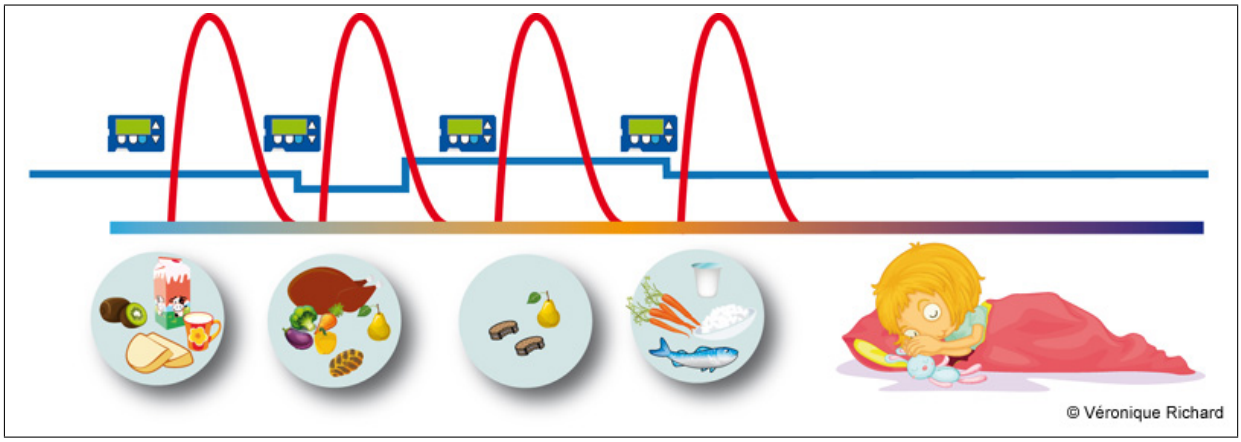


Figure 1.1: Diabetes treatment

6 Insulin

Insulin is a protein hormone secreted by the β cells of the pancreatic islets of Langerhans, as well as in the Brockmann bodies of some Teleost fish. It has a significant effect on the metabolism of carbohydrates, lipids, and proteins by promoting the absorption of glucose from the blood by adipose cells, liver cells, and skeletal muscle cells. The glucose absorbed by these tissues is converted into glycogen or triglycerides, or both simultaneously in the

case of the liver. The release of glucose by the liver into the blood is strongly limited by a high insulin concentration.

Consequently, this hormone, along with glucagon, plays a major role in the regulation of energy substrates, primarily glucose, fatty acids, and ketone bodies. In the insulin-glucagon relationship, insulin plays the primary role in mammals: its absence is fatal within a few months. In other species, particularly in birds, the opposite is true: glucagon is the primary hormone.

Overall, the action of insulin is often summarized by its hypoglycemic effect (reduction of blood glucose levels). It is probably more accurate to say that insulin is secreted according to nutritional status and physical activity, so that after meals, under the influence of elevated blood glucose levels, but also directly influenced by the presence of food in the digestive tract, insulin secretion is stimulated, allowing for the storage of glucose, the final product of carbohydrate digestion.[4]

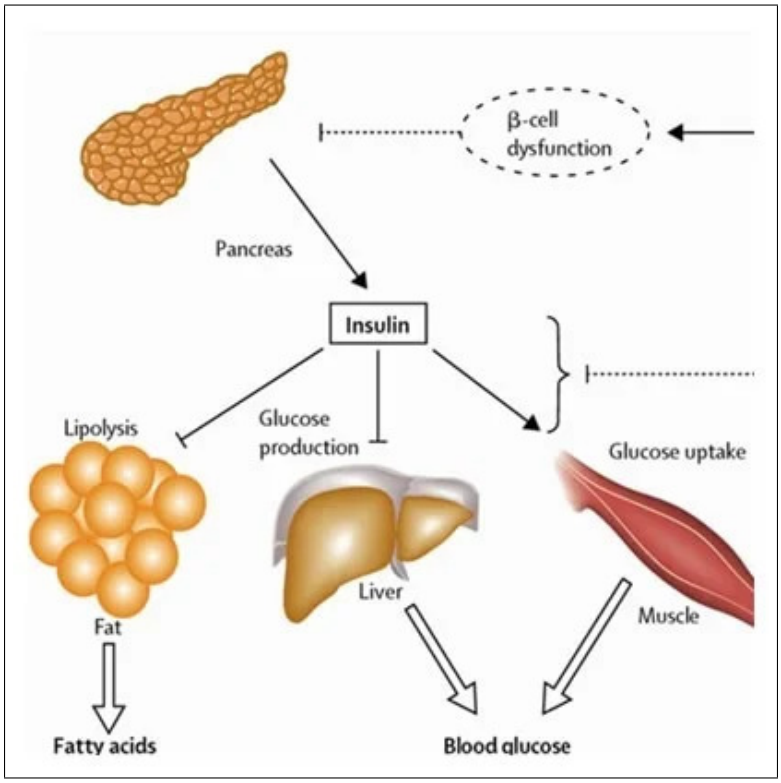


Figure 1.2: Insulin production

7 Insulin pump

An insulin pump is a medical device used for the administration of insulin in the treatment of diabetes mellitus, also known as continuous subcutaneous insulin therapy. The device configuration may vary depending on design. A traditional pump includes:

- The pump (including controls, processing module, and batteries)
- A disposable reservoir for insulin (inside the pump) Medical uses.
- A disposable infusion set, including a cannula for subcutaneous insertion (under the skin) and a tubing system to connect the insulin reservoir to the cannula. Other configurations are possible. More recent models may include disposable or semi-disposable designs for the pumping mechanism and may eliminate tubing from the infusion set. An insulin pump is an alternative to multiple daily injections of insulin by insulin syringes or an insulin pen and allows for flexible insulin therapy when used in conjunction with blood glucose monitoring and carbohydrate counting. [5]

8 Types of insulin pump

There are two types of insulin pump:

8.1 Tethered insulin pump

A tethered pump is attached to the body by another small tube that connects to the cannula. The pump itself usually has all the controls on it and can be carried on the belt, in a pocket, or in a body band. The patient can wear it under their clothes if they don't want it to be on show.
Tethered pumps can be different in things like colour, screen size and some have extra features like Bluetooth remotes.[5]

8.2 Patch insulin pump

The patient attach patch pumps directly on to the body where they've chosen to place their cannula. People tend to put them on their legs, arms or stomachs.
Patch pumps have no extra tubing, which means the pump sits directly on the skin and

it works by using a remote.

Unlike a tethered pump, patch pumps are disposable. the user need to change the whole device when the pump alerts them, not just the infusion set and location.[5]

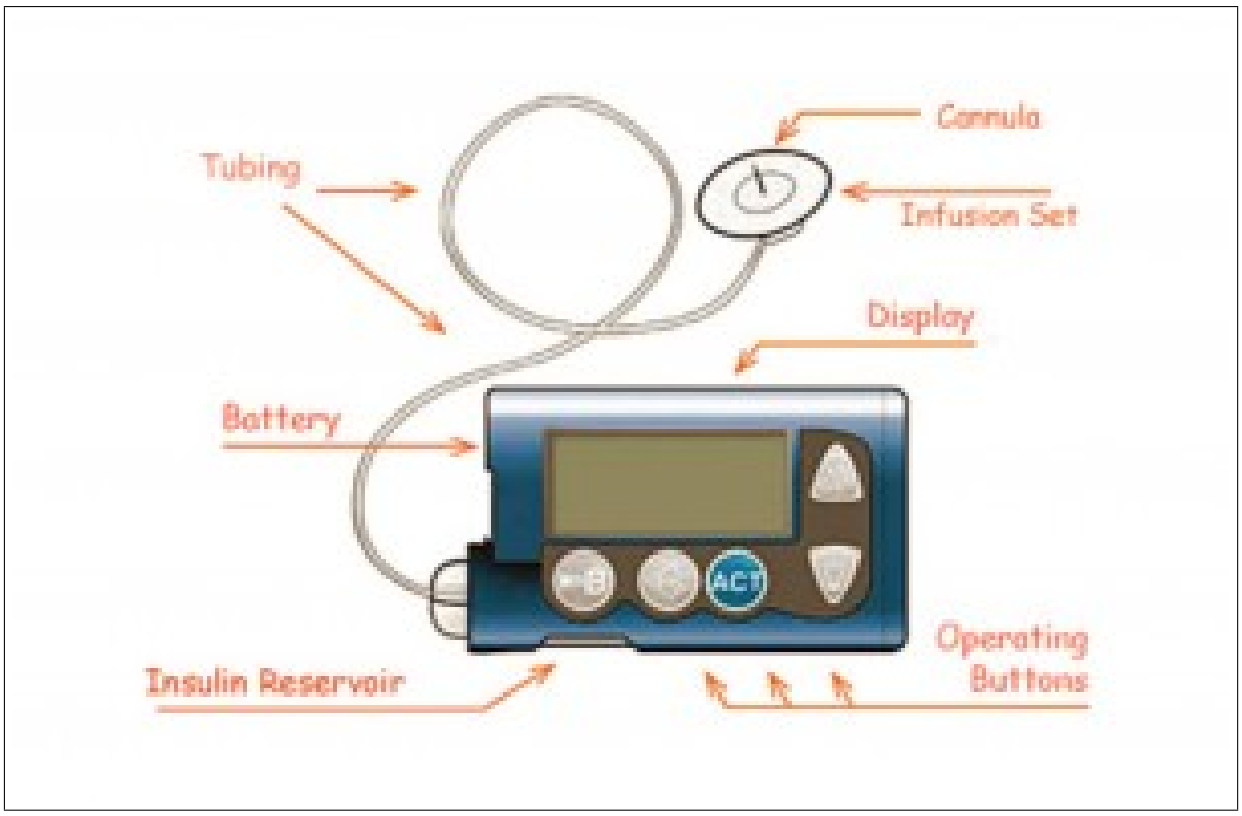


Figure 1.3: Insulin pump basics

9 Advantages

Users report better quality of life (QOL) compared to using other devices for administering insulin. The improvement in QOL is reported in type 1 and insulin-requiring type 2 diabetes subjects on pumps.

- The use of rapid-acting insulin for basal needs offers relative freedom from a structured meal and exercise regime previously needed to control blood sugar with slow-acting insulin.
- Programmable basal rates allow for scheduled insulin deliveries of varying amounts at different times of the day. This is especially useful in controlling events such as the

dawn phenomenon resulting in fewer and less severe low blood sugar events during the night.

- Many users feel that blousing insulin from a pump is more convenient and discreet than injection.
- Insulin pumps make it possible to deliver more precise amounts of insulin than can be injected using a syringe. This supports tighter control over blood sugar and hemoglobin A1c levels, reducing the chance of long-term complications associated with diabetes. This is predicted to result in long-term cost savings relative to multiple daily injections.
- Many modern insulin pumps have a ”bolus wizard” that calculates how much bolus insulin is needed, taking into account expected carbohydrate intake, blood sugar level, and still-active insulin.
- Insulin pumps can provide an accurate record of insulin usage through their history menus. On many insulin pumps, this history can be uploaded to a computer and graphed for trend analysis.
- Neuropathy is a troublesome complication of diabetes resistant to usual treatment. There are reports of alleviation or even total disappearance of resistant neuropathic pain with the use of insulin pumps.
- Recent studies of use of insulin pumps in Type 2 diabetes have shown profound improvements in HbA1c, sexual performance, and neuropathy pain. [6]

10 Accessibility

Use of insulin pumps is increasing because of:

- Easy delivery of multiple insulin injections for those using intensive insulin therapy.
- Accurate delivery of very small boluses, helpful for infants.
- Growing support among doctors and insurance companies due to the benefits contributing to reducing the incidence of long-term complications.

- Improvements in blood glucose monitoring. New meters require smaller drops of blood, and the corresponding lancet poke in the fingers is smaller and less painful. These meters also support alternate site testing for the most routine tests for practically painless testing.

11 History

With the development of partnerships between electronics firms and medical device manufacturers, medical devices have become increasingly miniaturized and functional throughout the decade.

In 1980, Medtronic introduced its first programmable pacemaker to the market.

Medical devices play a prominent role in diabetes management.

As early as 1969, Bayer introduced the first portable blood glucose measuring device.

The development of the concept of continuous insulin infusion in the 1970s was achieved by Professor Gérard Slama (Paris) and Professor John Pickup (London).

The first true insulin pump was introduced in Germany.

Figure 1.4: First insulin pump

In 1978, in the United Kingdom, John Pickup and his collaborators published an article mentioning the successful use of the insulin pump for a duration of 7 days. The Promedicus pump from Siemens is calibrated for insulin and delivers a constant basal rate. Before it, other pumps had already been commercialized in the late 1970s; these were already used for pain treatment for a long time but were not calibrated for insulin. In 1980, the flow rate adjustment was done by modifying the insulin and sodium chloride mixing ratios; the bolus was administered by turning a screw. A lack of precision that has been resolved and constantly improved since then, making the external insulin pump the "gold standard," the current reference, for the treatment of type 1 diabetes.
In 2002, Smiths Medical released the external pump Deltec Cozmo. It was withdrawn from the market in 2008 due to imperfections. And Cygnus announces the imminent arrival of the GlucoWatch, whose process is based on the evaluation of an electric current between electrodes placed on the patient's wrist. The 2-hour startup required during each calibration scheduled every 12 hours, the lack of reliability of the results (temperature changes, sweating, skin reaction), and the cost of consumables discouraged potential users. Two other "watches" will follow without further success: the Pendragon and the Glucoband. In 2005, with the Minimed Guardian, the patient can read their blood glucose results on a real-time display. In 2009, Abbott offers the FreeStyle Navigator continu In 2010, Novalab announces the distribution of the DexCom Seven Plus, which displays glucose values every 5 minutes for 7 days on a receiver the size of a cell phone. Medtronic introduces the Paradigm Veo™ pump, which allows for finer adjustment of pump responsiveness (0.025 vs. 0.05), particularly useful in young children, and a number of alarms allow for even more precise dose adjustments. A miniaturized autonomous artificial pancreas is implanted in a patient at the Montpellier University Hospital by Professors Renard and Bringer, with a result very close to normal. The device includes an implanted insulin pump, a continuous glucose monitoring device under the skin, and a control computer module installed in a cell phone. An Italian laboratory presents a new technique for reading blood glucose levels using a glycolaser at the European diabetes congress. The device uses a laser beam sent to the patient's finger. The accuracy of the device is not yet optimal but modifications are underway.

12 Today

Numerous insulin pumps are available on the market. However, this medical device remains relatively uncommon due to its very high price (minimum of 3000 euros). The main companies producing this type of device are Medtronic, Roche, and Novalab. The latest models offer real-time monitoring and data acquisition capabilities. The Animas insulin pump (Novalab) has an integrated CGM (Continuous Glucose monitoring) system. This system allows for the tracking of the amount of active bolus in the body, enabling better decision-making regarding insulin administration. There are also pumps connected to the glucose sensor to monitor the patient's levels. Other companies have opted for discretion by minimizing the size of the pump to make it less noticeable for the patient wearing it. This was the case with OmniPod, which committed to creating a discreet pump while ensuring its robustness and performance with pumps to be changed every 3 days. This pump is connected to a wireless PDM (Personal Diabetes Manager) that manages insulin administration, retrieves data from the integrated glucometer, calculates active insulin in the body, and can also suggest a bolus dose for the patient to inject.
Cellnovo aimed to create a discreet insulin pump that is also rechargeable, aiming to have the smallest possible impact on the environment.

Figure 1.5: The insulin pump today

13 Future developments

When insulin pump technology is combined with a continuous blood glucose monitoring system, the technology seems promising for real time control of the blood sugar level. Currently there are no mature algorithms to automatically control the insulin delivery based on feedback of the blood glucose level. When the loop is closed, the system may function as an artificial pancreas.

Insulin pumps are being used for infusing pramlintide (brand name Symlin, or synthetic amylin) with insulin for improved postprandial glycemic control compared to insulin alone.

Dual hormone insulin pumps that infuse either insulin or glucagon. In event of hypoglycemia, the glucagon could be triggered to increase the blood glucose. This would be particularly valuable in a closed loop system under the control of a glucose sensor. The Artificial Pancreas, currently in clinical trials for FDA approval, is a recently developed device designed with this technology in mind.

Ultrafast insulins. These insulins are absorbed more quickly than the currently available Humalog, Novolog, and Apidra which have a peak at about 60 minutes.Faster insulin uptake would theoretically coordinate with meals better, and allow faster recovery from hyperglycemia if the insulin infusion is suspended. Biodel is developing an ultrafast insulin.

14 Functioning

The insulin pump operates by delivering a continuous flow of insulin into the body through a small, flexible tube called a cannula, which is inserted under the skin. This continuous subcutaneous infusion mimics the function of a healthy pancreas, which continuously releases insulin in response to changing blood glucose levels. The pump is programmed to deliver both basal insulin, which provides a steady background level of insulin throughout the day and night, and bolus insulin, which is administered to cover meals or correct high blood sugar levels. The user can adjust the basal rates and administer bolus doses according to their individual insulin needs, providing precise control over blood glucose levels. Advanced insulin pumps may also feature integrated continuous glucose monitoring systems, allowing for real-time monitoring of blood sugar levels and automatic adjustments to insulin delivery based on sensor readings.
[7]

15 Components

15.1 Motor

Insulin pumps use a small motor to drive a piston or other mechanism that pushes insulin from the reservoir through the infusion set and into the body. The microprocessor controls the motor's speed and direction to deliver precise doses of insulin according to the user's settings.

15.2 Leadscrew

One end of the leadscrew is usually connected to the shaft of the motor. When the motor rotates, it turns the leadscrew, initiating the linear movement of the nut along the screw.

15.3 Piston

In insulin pumps, the leadscrew is typically connected to a piston or plunger located within the reservoir. As the nut moves along the leadscrew, it pushes the piston, displacing insulin from the reservoir and directing it towards the infusion set for delivery into the body.

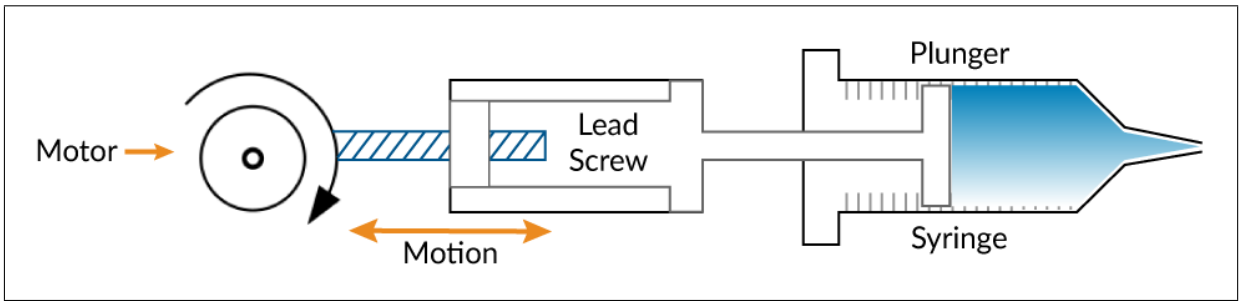


Figure 1.6: The principle functionning of an insulin pump

15.4 Microprocessor

The microprocessor is the brain of the insulin pump, responsible for controlling all of its functions. It executes software algorithms to manage insulin delivery based on programmed settings and sensor readings. The microprocessor interprets user input from the

interface and communicates with other components of the pump, such as the motor and sensors.

15.5 Interface Components

The user interface, including the screen, buttons, or touchscreen, contains electrical components such as LED displays, touch sensors, and circuitry for user interaction. The microprocessor processes input from the interface and controls the display of information to the user.

15.6 Sensors and Alarms

Some insulin pumps come with built-in continuous glucose monitoring (CGM) sensors, which continuously measure blood sugar levels. These pumps can automatically adjust insulin delivery based on the user's blood sugar levels and can alert the user to high or low blood sugar levels with alarms.

15.7 Safety Features

Insulin pumps often incorporate safety mechanisms to prevent over-delivery or under-delivery of insulin, such as limit switches or position sensors that monitor the movement of the leadscrew and piston. These features help ensure the reliability and safety of the insulin delivery system.

16 Conclusion

In this chapter, we navigated the landscape of diabetes, delineating its nuances and the imperative for effective management. Through exploration of diagnostic criteria and treatment options, including the innovative use of insulin pumps, we underscored the importance of tailored approaches to diabetes care. Looking ahead, the integration of insulin pump technology with continuous glucose monitoring systems holds promise for enhancing patient outcomes, heralding a new era in diabetes management.

Chapter 2
Insulin pump modeling

1 Introduction

This chapter will primarily concentrate on modeling the insulin pump by developing mathematical models based on governing physical laws for each component: the DC motor, the speed reducer, the screw-nut mechanism, and the piston-cylinder assembly, These models will be briefly explained, and the simulations will be given along with the corresponding SIMSCAPE models. In order to ensure an accurate depiction of the operational dynamics of the pump.

2 System description

The integration of three disciplines is essential for the development of a reliable, safe, and user-friendly insulin pump. The electronic system manages the overall control and monitoring, the mechanical system handles the physical delivery of insulin, and the hydraulic system ensures the proper fluid dynamics for an accurate and a consistent insulin delivery.

The figure below represents the insulin-pump mechanism :

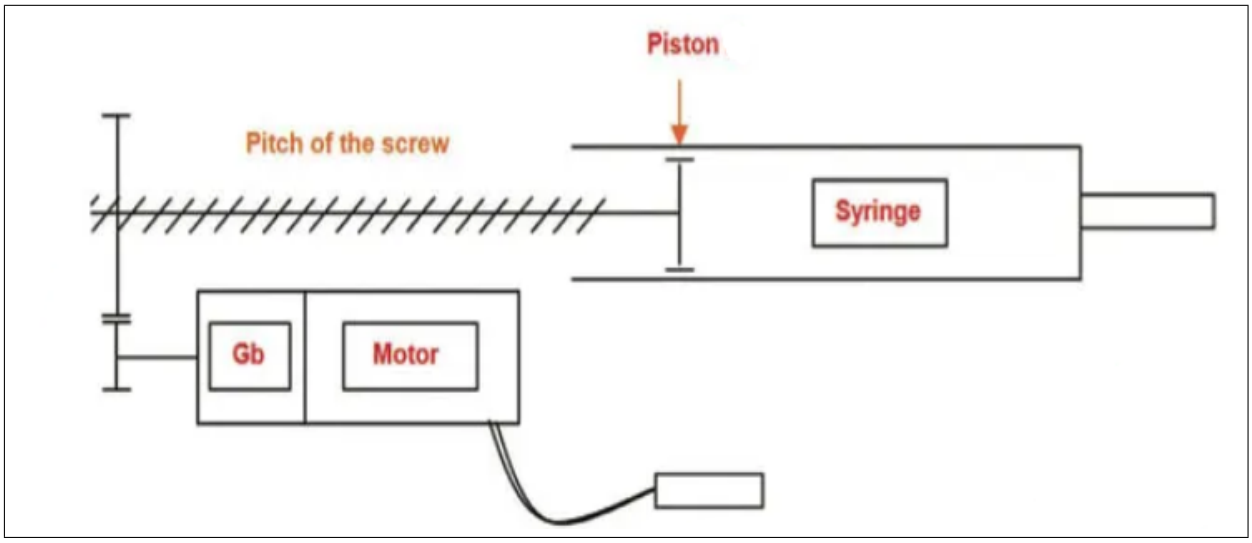


Figure 2.1: Insulin pump schema

3 DC motor with permanent magnet

The DC motor (Direct curent motor) is one of the first machines used to convert electrical power into mechanical power. The DC motor uses electricity and a magnetic

field to produce torque, which gives rotational speed. There are different kinds of D.C. motors, but they all work on the same principles. Basic working principle of DC motor is based on the fact that whenever a current carrying conductor is placed inside a magnetic field, there will be mechanical force experienced by that conductor.

Hence for constructing a DC motor it is essential to establish a magnetic field. The magnetic field is obviously established by means of a magnet. The magnet can be an electromagnet or permanent magnet. When a permanent magnet is used to create a magnetic field in a DC motor, the motor is known as permanent magnet dc motor or PMDC motor. The PMDC Motors do not require field windings. In addition, they have a small size and cheaper. On the other hand, Permanent magnets cannot produce a high flux density as that as an externally supplied shunt field does. Also, the magnetic field of PMDC motor is present at all time, even when the motor is not being used. The PMDC motors are used in different applications ranging from fractions to several horse powers. They are developed up to about 200 kW for use in many industries. PMDC motors are mainly used in automobiles to operate windshield wipers and washers, to raise the lower windows, to drive blowers for heaters and air conditioners. They are also used in computer drives, toy industries, electric toothbrushes, portable vacuum cleaners, food mixers, wheelchairs, door openers and other applications. [8]

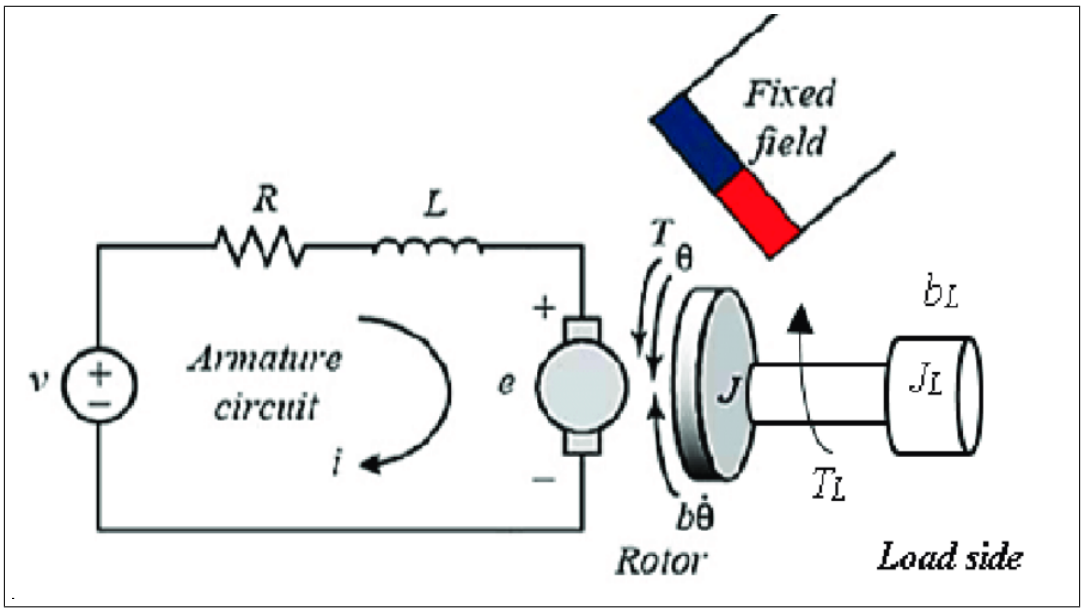


Figure 2.2: Schematic diagram of DC motor

3.1 DC motor components

The field winding

It called the stator, consists of a permanent magnet that generates a magnetic field whose flux Φ passes through the rotor. It remains constant if the excitation current I passing through it remains constant.

The Armature

It called the rotor, it is composed of a winding that has a certain resistance R and an inductance L. During rotation, the turns of this winding are crossed by a variable flux and generate an electromotive force (EMF) that can be considered continuous due to the large number of conductors.

The Brushes

The brushes ensure the passage of electric current between the power supply and the windings of the armature in the form of friction al contact. The brushes are made of graphite and are, in a way, the wearing part. As the graphite wears out, it releases dust that makes the direct current motor sensitive to proper maintenance and therefore costly.

3.2 Why the DC motor?

- Precise control: DC motors offer very good control over speed and torque. This is crucial for an insulin pump, where delivering the exact amount of insulin is critical. A slight variation in speed could result in too much or too little insulin being delivered, which can be dangerous for the user.
- Reliability: Insulin pumps are life-critical devices, so they need to be dependable. DC motors have a well-established reputation for reliability, making them a good fit for this application.
- Efficiency: Since insulin pumps are battery-powered, efficient operation is essential. DC motors can be designed to be very energy-efficient, which helps to extend battery life and minimize the number of battery replacements needed.

- Size: Insulin pumps are small and discreet devices. DC motors, particularly coreless DC motors, can be very compact, allowing them to fit comfortably within the pump's housing.
- Quiet operation: Insulin pumps are often worn by users throughout the day and night. DC motors are generally quiet, which helps to ensure user comfort and discretion.[9]

The motor must meet very high requirements: to minimize the weight of the portable device, it must be compact with a diameter not exceeding approximately 10 millimeters. However, the motor must also be reliable and precise, as delivering too little or too much insulin is dangerous for the patient. A human life may even depend on the reliability of the motor used. Given that insulin injections into the body must be repeated every few hours, the motor must start and stop at regular intervals. Additionally, since it runs on battery power, the motor must do so very efficiently.

3.3 FAULHABER micromotor

DC micro-motors, particularly those utilizing precious metal commutation like those from Faulhaber, are commonly employed in medical applications for several reasons, the combination of reliability, compactness, precision, low EMI, longevity, and sometimes biocompatibility makes them highly suitable, the figure below represents the datasheet of this kind of motor.

Series 0816 ... SR

Values at 22°C and nominal voltage		0816 K	003 SR	006 SR	009 SR	012 SR	
1	Nominal voltage	U_N	3	6	9	12	V
2	Terminal resistance	R	5,4	21,2	47	101,8	Ω
3	Efficiency, max.	$\eta_{max.}$	69	69	69	67	%
4	No-load speed	n_0	13 250	13 500	13 500	12 600	min^{-1}
5	No-load current, typ. (with shaft ø 1 mm)	I_0	0,016	0,0083	0,0057	0,0039	A
6	Stall torque	M_H	1,15	1,13	1,15	1	mNm
7	Friction torque	M_R	0,034	0,034	0,035	0,034	mNm
8	Speed constant	k_n	4 526	2 318	1 543	1 085	min^{-1}/V
9	Back-EMF constant	k_E	0,221	0,431	0,648	0,922	mV/min^{-1}
10	Torque constant	k_M	2,11	4,12	6,19	8,8	mNm/A
11	Current constant	k_I	0,474	0,243	0,162	0,114	A/mNm
12	Slope of n-M curve	$\Delta n/\Delta M$	11 475	11 904	11 714	12 553	min^{-1}/mNm
13	Rotor inductance	L	53	217	507	1 033	µH
14	Mechanical time constant	τ_m	6,1	6,5	6,2	6,5	ms
15	Rotor inertia	J	0,051	0,052	0,051	0,049	gcm²
16	Angular acceleration	$\alpha_{max.}$	229	219	227	203	·10³rad/s²
17	Thermal resistance	R_{th1} / R_{th2}	20 / 48				K/W
18	Thermal time constant	τ_{w1} / τ_{w2}	4,2 / 242				s
19	Operating temperature range:						
	– motor		-30 ... +85 (optional version -30 ... +125)				°C
	– winding, max. permissible		+85 (optional version +125)				°C
20	Shaft bearings		sintered bearings				
21	Shaft load max.:						
	– with shaft diameter		1				mm
	– radial at 3 000 min^{-1} (1,5 mm from bearing)		0,7				N
	– axial at 3 000 min^{-1}		0,1				N
	– axial at standstill		20				N
22	Shaft play:						
	– radial	≤	0,02				mm
	– axial	≤	0,2				mm
23	Housing material		steel, nickel plated				
24	Mass		4,5				g
25	Direction of rotation		clockwise, viewed from the front face				
26	Speed up to	$n_{max.}$	16 000				min^{-1}
27	Number of pole pairs		1				
28	Magnet material		NdFeB				

Figure 2.3: FAULHABER DC micromotor datasheet

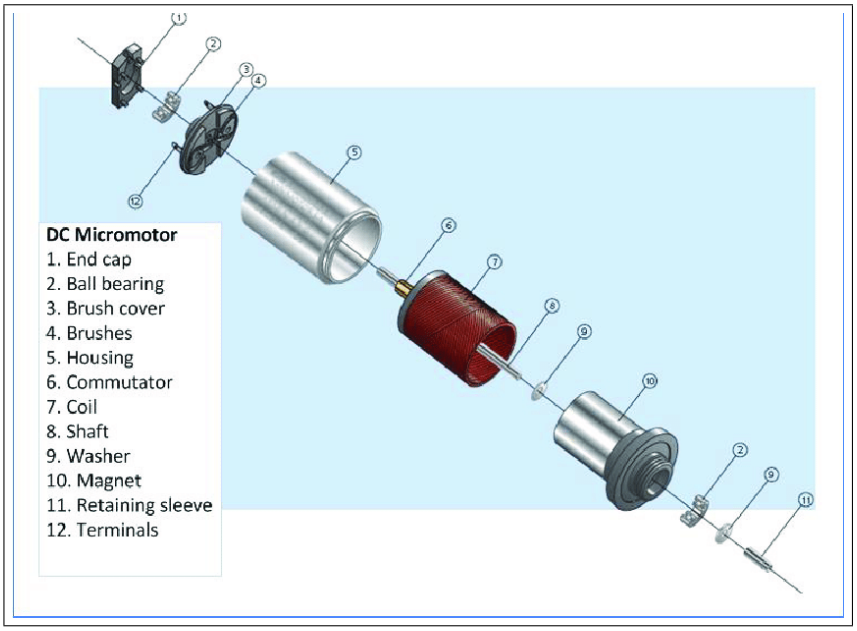


Figure 2.4: FAULHABER DC-micromotor

3.4 The modeling of DC motor

The characteristic equations of the DC motor engine are given by these relations below According to Kirchhoff's law, we have:

$$U(t) = E(t) + R \cdot I(t) + L\frac{dI(t)}{dt} \tag{2.1}$$

$$E(t) = Ke \cdot \omega_m(t) \tag{2.2}$$

$$J \cdot \frac{d\omega_m(t)}{dt} = C_m(t) - C_r(t) - f\omega_m(t) \tag{2.3}$$

$$C_m(t) = K_m \cdot I(t) \tag{2.4}$$

With :

$U(t)$ = voltage applied to the motor terminals $[V]$

$E(t)$ = electromotive force $[V]$

$I(t)$ = current $[A]$

$Cm(t)$ = motor torque $[N.m]$

$Cr(t)$ = the resistant torque $[N.m]$

$\omega m(t)$ = the motor rotation speed $[rad/s]$

R = the resistance of the motor armatures $[\Omega]$

L = the inductance of the motor armatures $[H]$

J = the inertia of the motor $[kg.m\ 2]$

f= coefficient of friction $[N.m.s]$

Km = engine torque constant $[N.m/A]$

Ke = electromotive force constant $[V.s/rad]$

The DC motor system of equations is a system of coupled differential equations, difficult to solve in this form, but by applying a Laplace transform to them, these equations become algebraic and the system is linear.

3.5 SIMSCAPE DC motor model

The figure below represents the DC motor model using SIMSCAPE of MATLAB driven by a constant input signal that approximates a pulse-width modulated signal, in order to visualize the current and the speed of the motor.

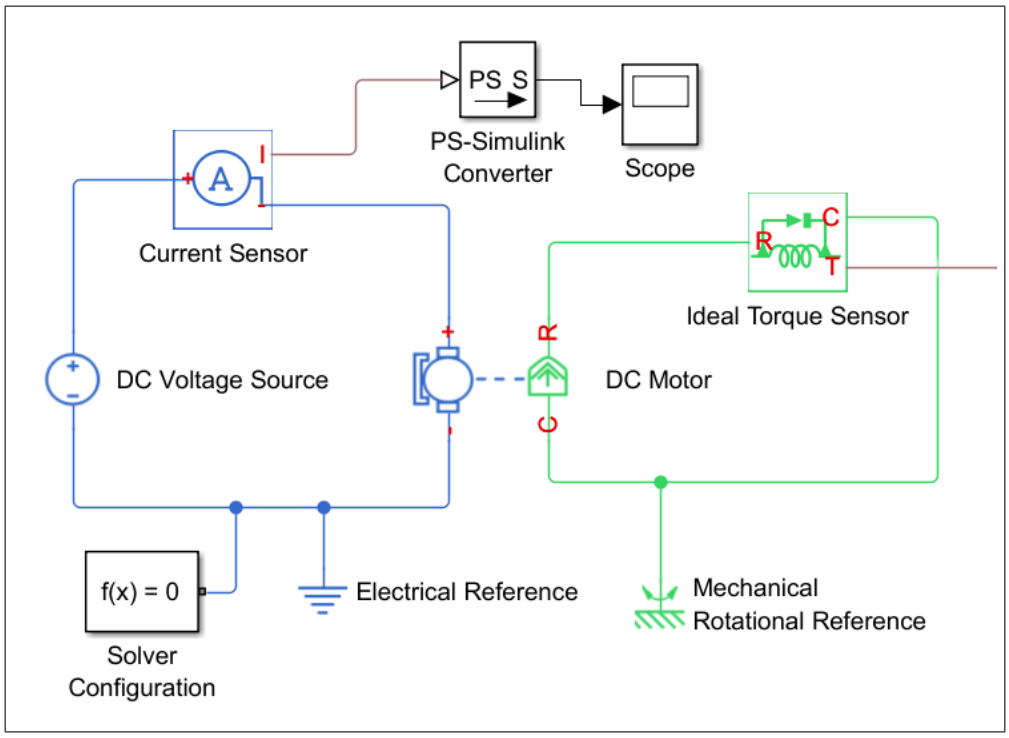


Figure 2.5: DC motor SIMSCAPE model

3.6 The simulation result

After reviewing the datasheet of the DC motor, it is evident that for the desired motor speed of 1319 *rad/sec* (which is the equivalent of 12600 (*rpm*) , powered by a 12 (V) supply, careful consideration of the motor specifications is necessary. By analyzing the motor's torque-speed characteristics and voltage-speed relationship, it becomes apparent that achieving the desired rotational speed is possible using this model.

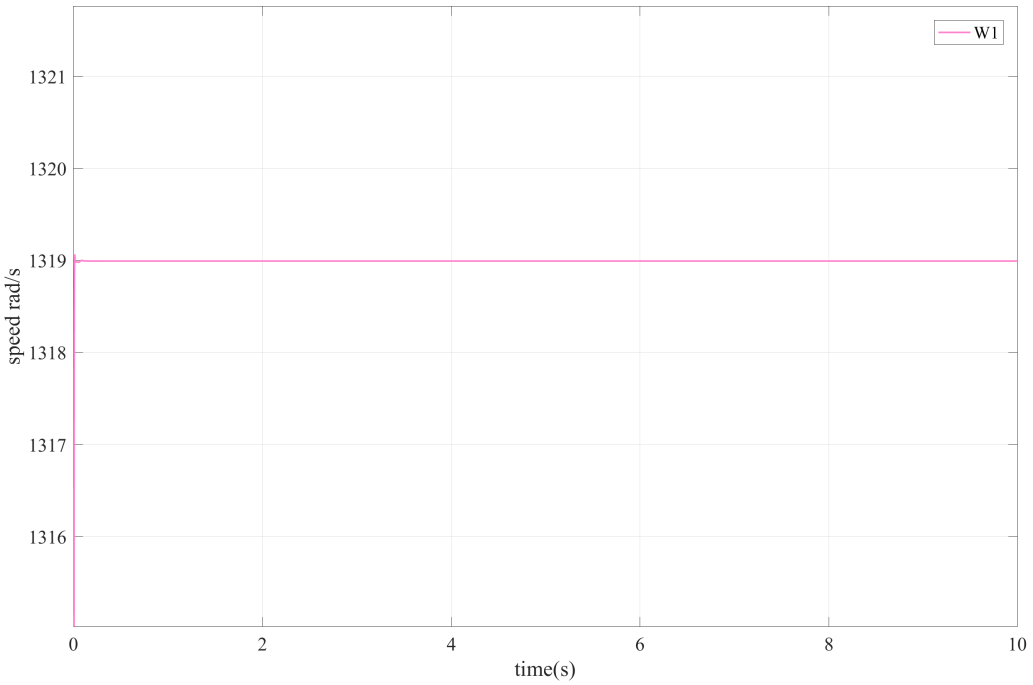
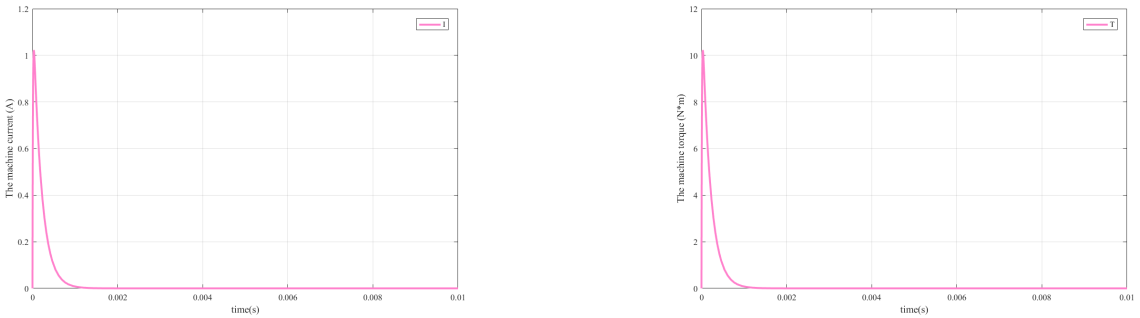


Figure 2.6: DC motor speed curve

So as it shown in the simulation result, the curve amplitude is 1319 *rad/s*, exactly as required.



(a) The DC motor current curve **(b)** The DC motor torque curve

Figure 2.7: The DC motor electrical quantities graphs

The Torque and Current has significant relationship as in Figure 2.7 and 2.8,Torque and current show the same pattern but the current is much smaller scale. Thus, armature current can be used instead of Torque as input reference to the close Loop Feedback control.

Direct current (DC) series motors have a higher starting torque compared to other types of motors, and their power is in the kilowatt range.

4 Gear box

It is mechanical unit or component consisting of a series of integrated gears within a housing. In fact, the name itself defines what it is a box containing gears. In the most basic sense, a gearbox functions like any system of gears; it alters torque and speed between a driving device like a motor and a load.[10]

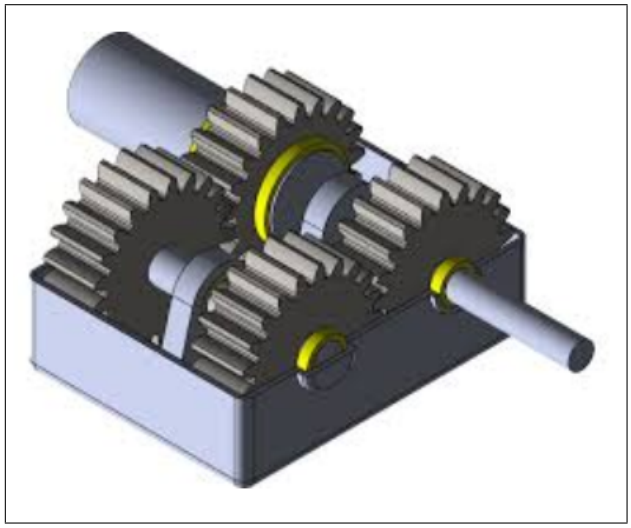


Figure 2.8: AI schema of gear box

4.1 Gear box modeling

The gearbox is designed to decrease speed (ωe) and increase the torque (Ce) of a motor shaft.

It aims to rotate a receiving component with a new torque (Ce) and speed ($Ce<Cs$ and $\omega e<\omega s$).

$$P_e = C_e \cdot \omega_e \tag{2.5}$$

$$P_s = C_s \cdot \omega_s \tag{2.6}$$

$$T = \frac{\omega_s}{\omega_e} \cdot \eta \cdot \frac{C_e}{C_s} \tag{2.7}$$

With :

ωe = Angular velocity of the motor shaft (input to the gearbox)[rad/s]
ωs = Angular velocity of the receiving component (output from the gearbox) [rad/s]
Ce = Torque of the motor shaft (input to the gearbox [$N.m$]
Cs = The resistant torque [$N.m$]
Pe = Power of the motor shaft (input to the gearbox) [$Watts$]
Ps = Power of the receiving component (output from the gearbox) [$Watts$]
T = Torque function [H]
η = Efficiency of the gearbox

4.2 Gear box SIMSCAPE model

After creating the DC motor block, it has to be connected with a mechanical gear box in order to reduce the machine speed.

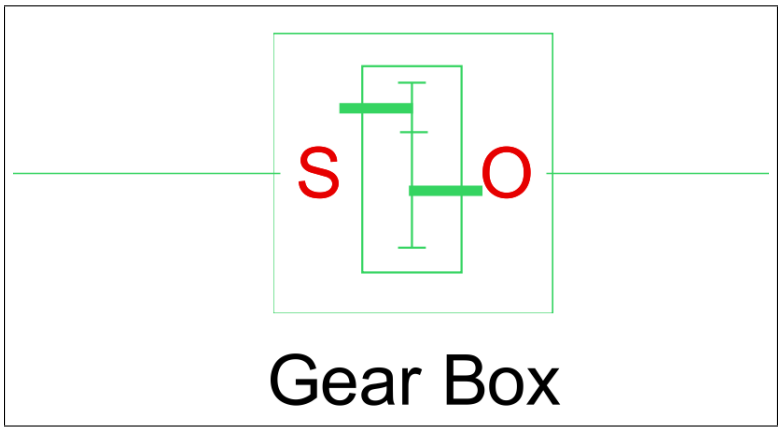


Figure 2.9: The gear box SIMSCAPE model

4.3 Simulation result

The gear box gain was 54, so the new motor speed has to be as following :

$$\omega e = k * \omega s \tag{2.8}$$

Which means :

$$\omega s = 1319/54$$

$$\omega s = 24.425 \quad rad/s$$

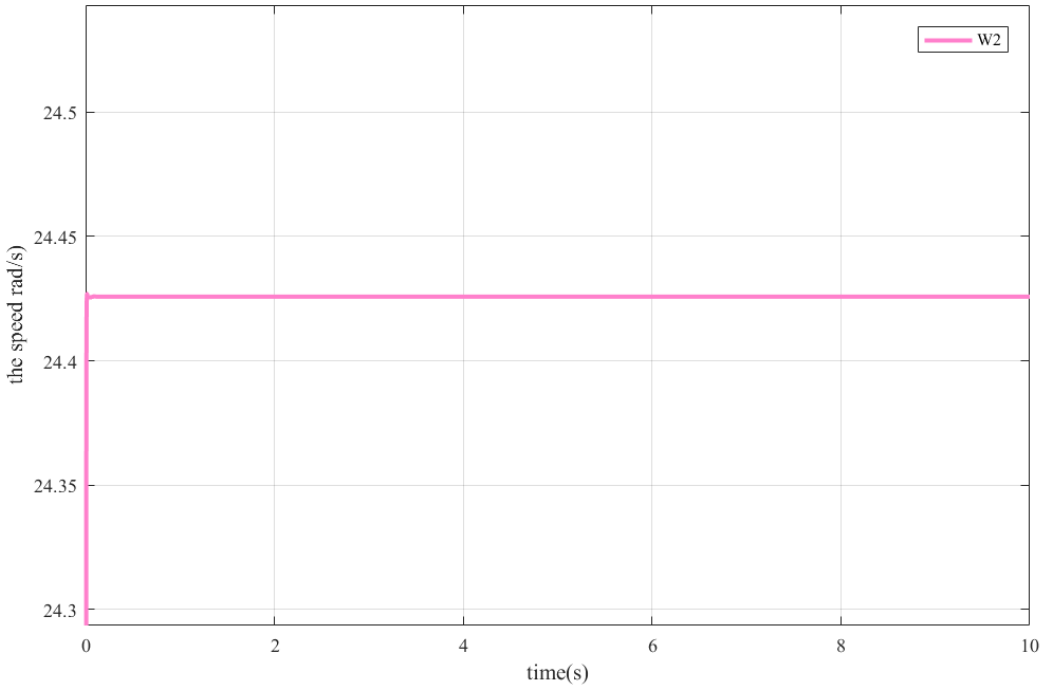


Figure 2.10: DC motor speed curve after connecting a gear box

The DC motor motion has reached its required value which means that the gear box is working perfectly.

5 Lead-screw

A lead screw is sometimes referred to as a “power screw” or a “translation screw”. They are used within motion control devices to transform rotary or turning movements into linear movements.Lead screws are threaded bars of metal and a threaded nut which is in direct contact with the screw; this generates sliding friction as opposed to rolling friction from other alternative devices (such as a ball screw). Rotational motion will turn the screw, causing the nut to move along in a linear motion. This, therefore, converts the motion from rotary to linear.

They can be used for either vertical or horizontal movements and can use linear glides for support where necessary. They can be operated either manually or mortised depending

on the application in hand.

Lead-screw are often used in high-performance linear motion systems because they provide a transmission with a relatively high stiffness and an inherent drive reduction. Low-friction ball or roller screws provide acceptably smooth motion for many applications because of elastic averaging among many balls or rollers in simultaneous contact.[11]

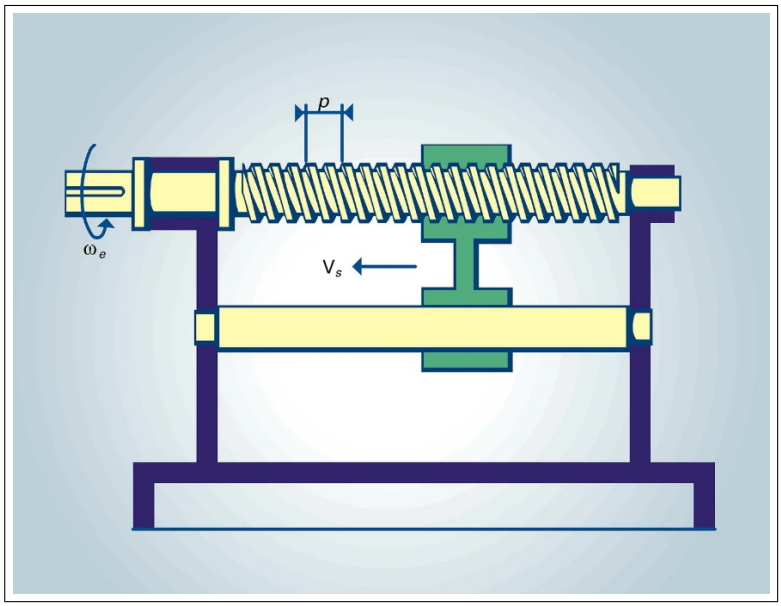


Figure 2.11: Demonstrative schema of the lead screw

5.1 Kinematic Relations

$$P = n \cdot P_x \tag{2.9}$$

Kinematic Relations:

$$X = \frac{P}{2\pi} \cdot \theta \tag{2.10}$$

$$V = \frac{P}{2\pi f} \tag{2.11}$$

$$V = \frac{P}{60N} \tag{2.12}$$

With :

P= Lead of the screw $[m]$

n= Number of starts or lead threads on the screw (dimensionless)

Px= Pitch of the screw $[m]$

X= Linear displacement of the nut $[m]$
θ= Angular displacement of the screw $[rad]$
V= Linear velocity of the nut $[m/s]$
f= Angular velocity of the screw $[Hz]$ or $[rad/s]$
N= Rotational speed of the screw $[rpm]$

5.2 Screw stiffness

Lead screw stiffness refers to the rigidity or resistance of a lead screw system to deflection or deformation under an applied load. It is a crucial mechanical property that influences the accuracy, repeatability, and overall performance of the system.
The stiffness of a lead screw system depends on various factors, including

- Material Properties
- Geometric Design
- Preload
- Environmental Conditions

5.3 The lead screw modeling

The modeling of the lead screw with taking stiffness (K) into account

$$T = K \cdot \theta \tag{2.13}$$

$$\theta = \int W \tag{2.14}$$

$$T = K \cdot \int W \tag{2.15}$$

$$T_c = K^* \int (W_{stif} - W_{piston}) dt \tag{2.16}$$

$$K = \frac{A \cdot E}{L} \tag{2.17}$$

$$T_s = \frac{P}{2\pi} \cdot F_p \tag{2.18}$$

$$F_p = T_s \cdot \frac{2\pi}{step} \tag{2.19}$$

$$W_{\text{piston}} = V_{\text{piston}} \cdot \frac{2\pi}{step} \tag{2.20}$$

With:

T = Torque [N·m]

K = Stiffness coefficient $[N{\cdot}m/rad]$

θ = Angular displacement $[rad]$

W = Work $[J]$

Tc = Compensating torque $[N{\cdot}m]$

K = Compensating stiffness coefficient $[N{\cdot}m/rad]$

$Wstif$ = Stiffness work $[J]$

$Wpiston$ = Piston work $[J]$

t = Time $[s]$

A = Cross-sectional area $[m2]$

E = Young's modulus $[Pa]$

L = Length $[m]$

Ts = Torque of the screw $[N{\cdot}m]$

Fp = Force of the piston $[N]$

P = Lead of the screw $[m]$

Fp = Angular frequency of the piston $[rad/s]$

$Vpiston$ = Velocity of the piston $[m/s]$

5.4 The lead screw SIMSCAPE model

The figure below represents the SIMSCAPE model of the lead-screw of the system connected to the gear box terminal.

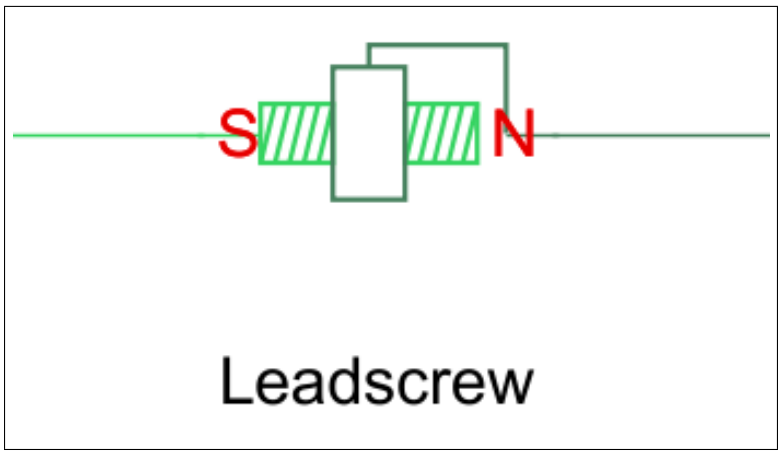


Figure 2.12: The lead screw SIMSCAPE model

5.5 Simulation result

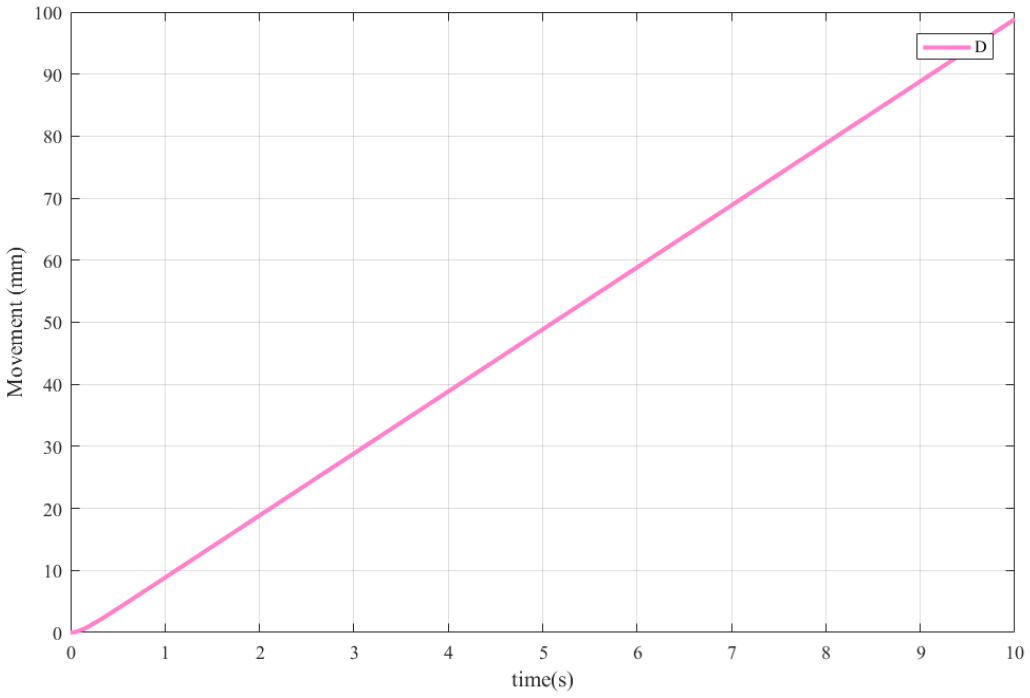


Figure 2.13: the nut movement curve

This curve represents the displacement of the nut (m) over time (s), and from its shape, it's clear that the nut translational movement increases when the motor start to rotate, in accordance with the operation of this system, this movement is what known as the step.

6 Piston and cylinder

A piston-cylinder system typically refers to a mechanical setup consisting of a piston enclosed within a cylinder. This system is commonly used in various engineering applications, such as internal combustion engines, hydraulic systems, and pneumatic systems, like pumps.

In this setup, the piston is a movable component that fits snugly inside the cylinder. When external forces, such as pressure or mechanical work, are applied to the piston, it moves along the length of the cylinder. This movement can be utilized to perform work or transfer energy within the system.

Piston-cylinder systems are fundamental components in many mechanical devices and serve various purposes depending on the specific application. For instance, . In hydraulic and pneumatic systems, piston-cylinder setups are used to generate or control fluid pressure, which can then be used to actuate other components or mechanisms.[12]

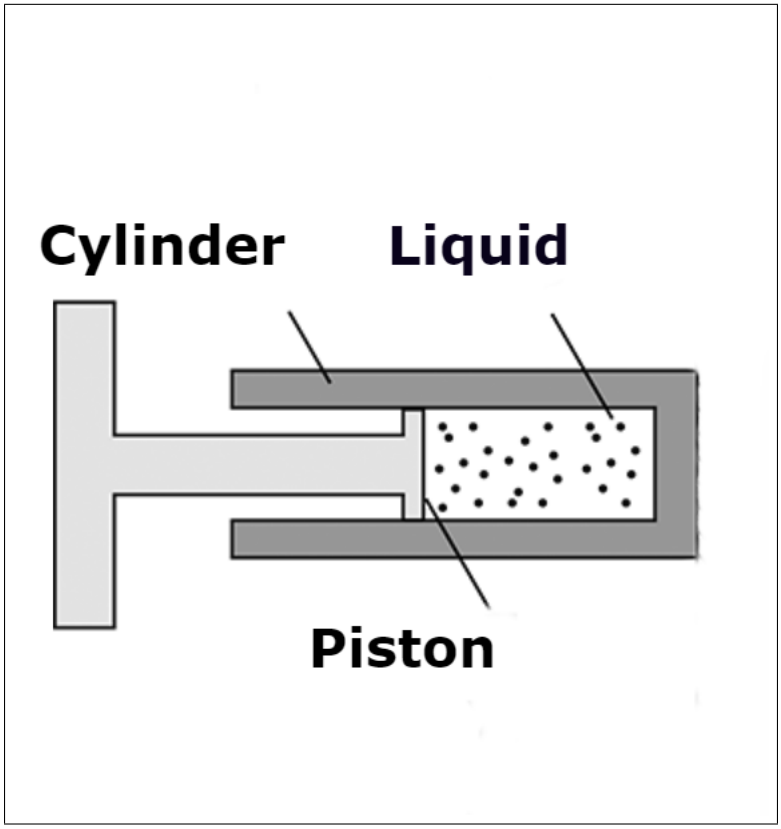


Figure 2.14: demonstrative schema of piston-cylinder system

6.1 The piston-cylinder modeling

Dynamic equations

$$\Sigma F_{\text{sys}} = M_p \cdot \frac{dV}{dt} \tag{2.21}$$

$$V = \frac{1}{M_p} \int F_{\text{sys}} dt \tag{2.22}$$

$$F_{\text{sys}} = F_p - F_f - F_{\text{res}} \tag{2.23}$$

$$F_f = R_c \cdot V \tag{2.24}$$

With:

$Fsys$ = Total system force $[N]$

Mp = Mass of the piston $[kg]$

V = Velocity of the piston $[m/s]$

t = Time $[s]$

Fp = Piston force $[N]$

Ff = Friction force $[N]$

$Fres$ = Resistive force $[N]$

Rc = Coefficient of friction $[N{\cdot}s/m]$

Hydraulic equations

$$Q = \frac{1}{R_{or}}(P_{\text{cyl}} - P_{\text{patient}}) \tag{2.25}$$

$$P_{\text{cyl}} = \frac{1}{C_{\text{cyl}}} \int (Q_{\text{pump}} - Q_{\text{patient}}) dt \tag{2.26}$$

$$Q_{\text{pump}} = V \cdot S_p \tag{2.27}$$

$$F_{\text{sys}} = P_{\text{cyl}} \cdot S_p \tag{2.28}$$

With:

Q = Volumetric flow rate $[m3/s]$

Ror = Hydraulic resistance $[Pa{\cdot}s/m3]$

$Pcyl$ = Cylinder pressure $[Pa]$

$Ppatient$ = Patient pressure $[Pa]$

$Ccyl$ = Cylinder compliance $[m3/Pa]$

$Qpump$ = Pump flow rate $[m3/s]$

$Qpatient$ = Patient flow rate $[m3/s]$

t = Time $[s]$

$Fsys$ = Total system force $[N]$

Sp = Piston surface area $[m2]$

6.2 Piston-cylinder SIMSCAPE model

The Piston-cylinder Simscape model is the final part of the pump as it's represented by a translational hydro-mechanical convertor working in its negative direction, connected with a hydraulic flow sensor to visualize the flow of insulin.

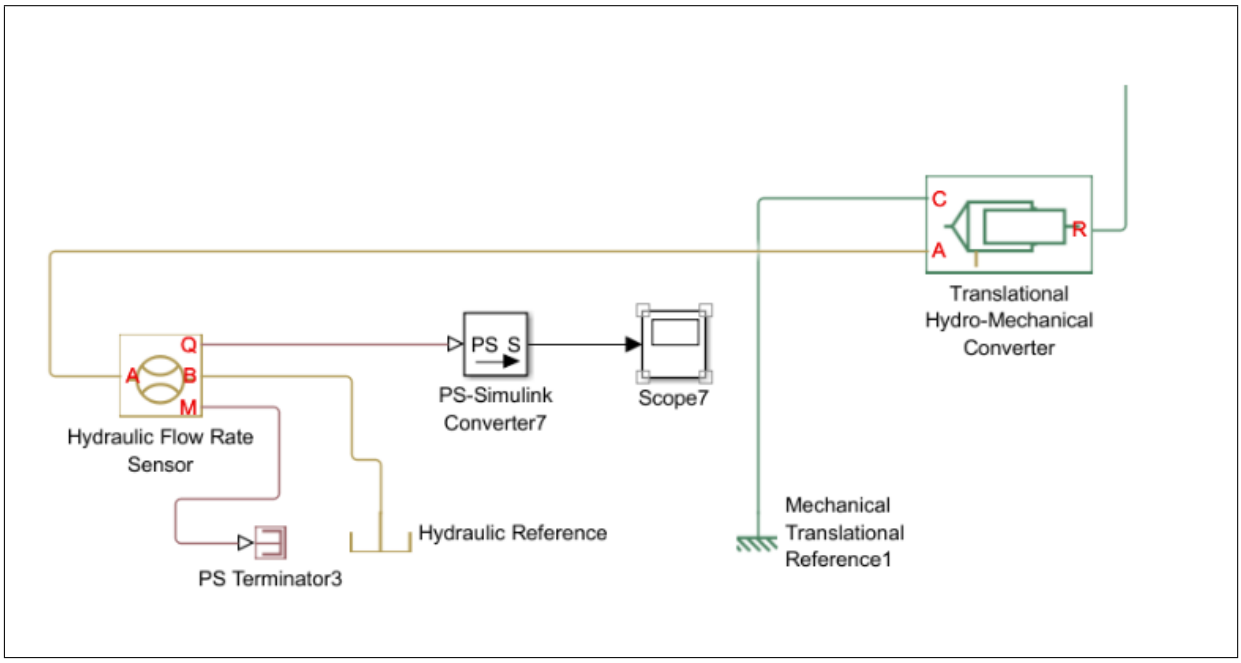


Figure 2.15: Piston-cylinder SIMSCAPE model

6.3 Simulation result

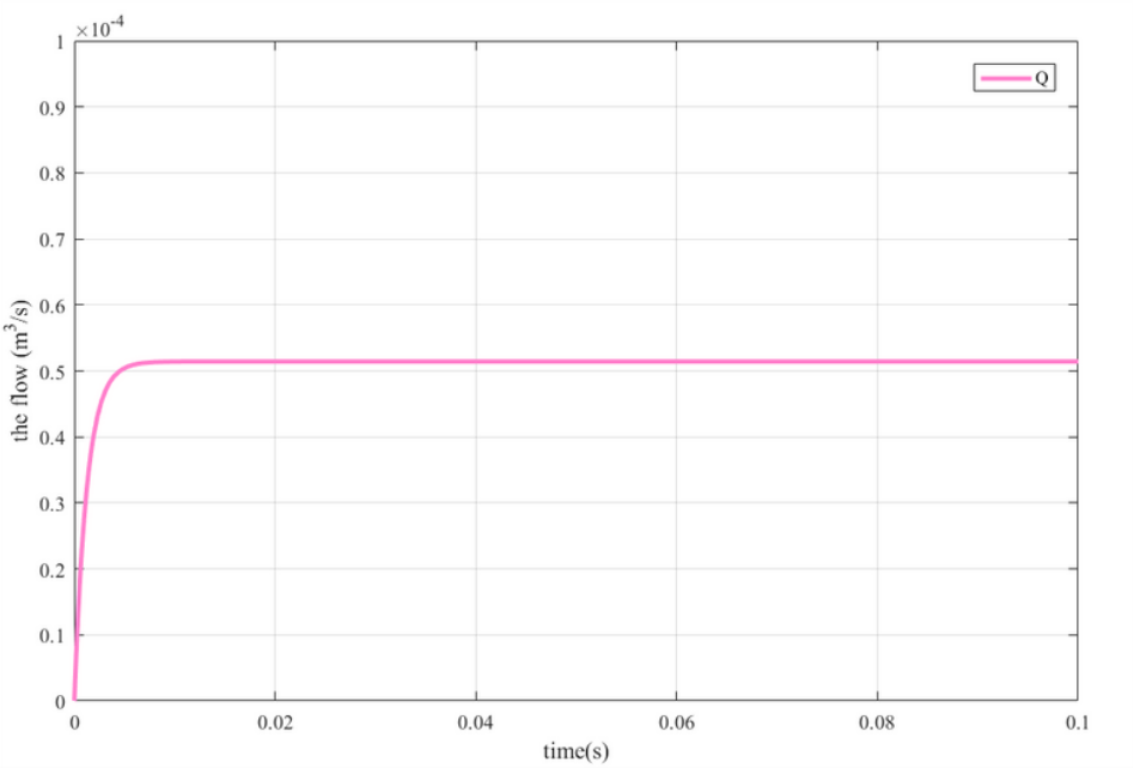


Figure 2.16: the flow curve

The flow curve is equivalent to the motor speed curve which means that the rotation of the motor provokes the flow of the liquid.

7 Conclusion

Through the lens of SIMSCAPE simulation, we have gained invaluable insights into the intricate dance of gears, DC motor, the lead screw and the piston-cylinder, that underpin the pump's operation. We have witnessed firsthand the seamless integration of these components, each playing a crucial role in ensuring the precise and reliable delivery of insulin to patients in need. From the precise speed afforded by the DC motor to the mechanical advantage provided by the gearbox and lead screw, arriving to the flow provided by the last component every element contributes to the pump's efficacy and efficiency.

Chapter 3
Insulin pump control

1 Introduction

While a typical way for diabetes therapy is discrete insulin infusion based on long-time interval measurement, in this chapter, the main goal is to design two models an open-loop system, and closed-loop model for continuous drug infusion to improve the traditional discrete methods and make diabetes therapy automatic in practice. By exploring the accumulative function of drug to insulin, a continuous injection model is proposed. Based on this model, proportional-integral-derivative *PID* controller is designed to tackle a control problem of the resulting highly nonlinear plant. Even with serious disturbance of glucose, such as nutrition absorption at meal time, the proposed schema can perform well in simulation experiments. To be able at the end to compare between the two scenarios.

2 An open-loop control

The physical design of the insulin pump must be small and lightweight. The reservoir and pump consist of a small syringe. A custom syringe plunger will slide linearly as the motor rotates a screw-nut system. The end of the syringe will have a connector to attach to a small tube leading to the subcutaneous catheter. The device must be capable of delivering bolus infusions of 1 to 15 units of insulin (U100) three times a day for at least three days before needing to be recharged or refilled. 15U x 3 doses x 3 days = 135U $\rightarrow$ a reservoir with a minimum capacity of 200U (2ml reservoir) is needed.

2.1 SIMULINK model

The figure below shows the SIMSCAPE model representing the basal functioning.

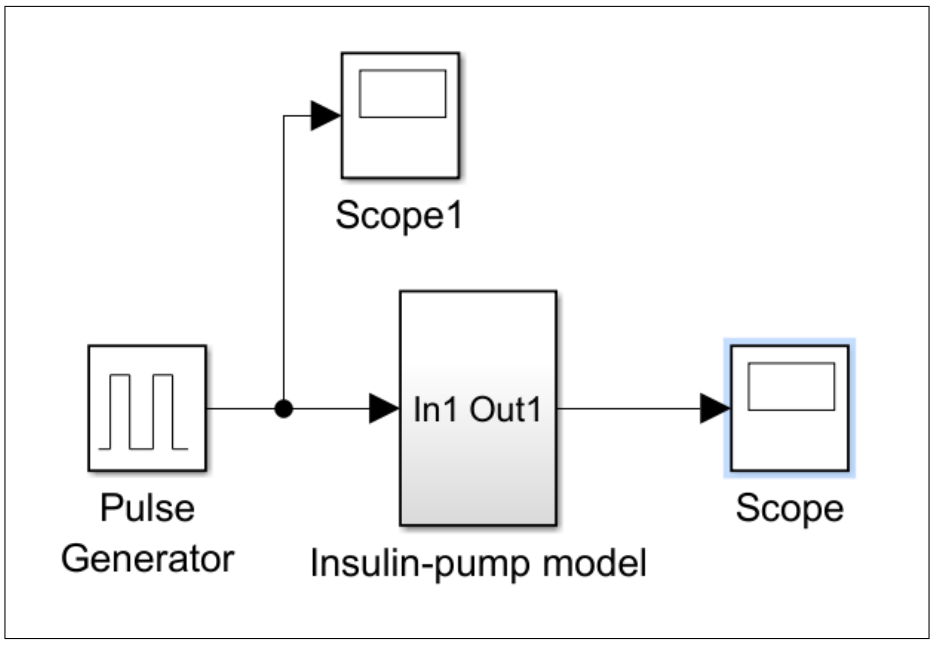
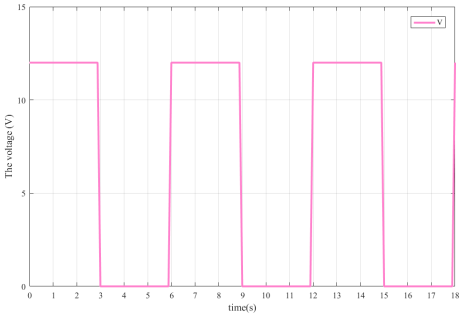
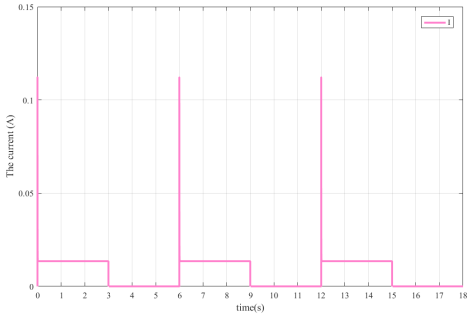


Figure 3.1: SIMSCAPE open-loop model

2.2 Simulation results



(a) The DC motor voltage subbly curve

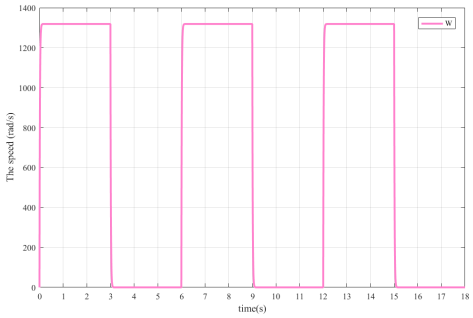


(b) The DC motor current curve

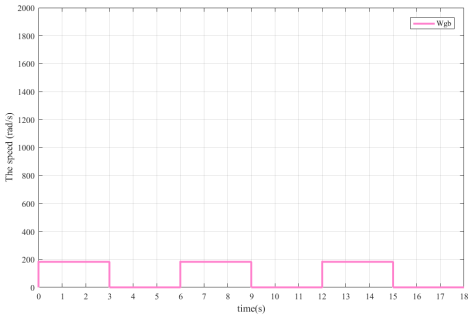
Figure 3.2: Open-loop DC motor electrical quantities graphs

The variation of speed (rpm) as a function of time (s) is almost identical to the variation of voltage (V), which means that the DC motor operates at nominal speed when it is powered.

The motor current reaches its maximum value when the motor is powered; otherwise, it drops to zero



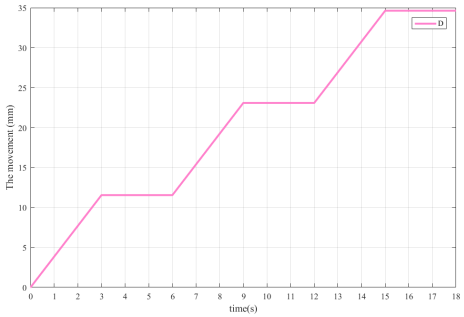
(a) The DC motor speed curve



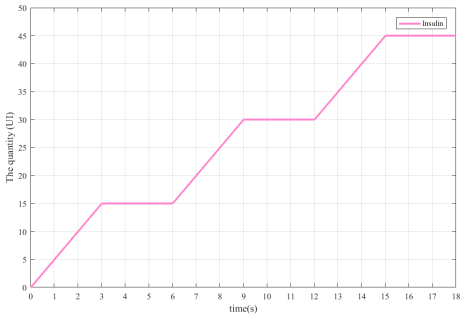
(b) The DC motor shaft speed curve

Figure 3.3: The DC motor speed before and after connecting a gear box

The provided graphs illustrate the speed behavior of a motor and its corresponding gearbox output over time. The motor speed was between 1600 rad/s and 0 rad/s in a cyclical pattern,This cyclical operation is mirrored by the gearbox output speed, which fluctuates between 200 rad/s and 0 rad/s, this rotation value was obtained by adjusting the gear box with gain of 57, indicating a reduction ratio that makes the system under a controlled operation, for certain purposes, with the gearbox perfectly reducing the speed as desired while maintaining synchronization with the motor's cyclic behavior.



(a) The nut movement curve



(b) The insulin quantity curve

Figure 3.4: Open-loop performance results of the nut and the piston-cylinder

The graph depicts the quantity of insulin delivered over time, showing a step wise increase in insulin units *(UI)*. This suggests that the insulin pump administers insulin in discrete increments. The nut movement in the insulin pump, driven by the motor, controls the delivery of insulin. When the motor is powered, it rotates, causing the nut to move linearly along a threaded rod. This linear motion pushes the insulin reservoir,

incrementally dispensing insulin into the body. The motor's cyclic activation, as shown in the previous speed graphs, directly translates to the controlled and precise delivery of insulin, ensuring accurate dosing as required by the user.

3 A continuous closed-loop control

To describe the complete metabolism process of glucose in patients with type I diabetes, three key parameters must be considered: drug dosage, insulin concentration, and glucose concentration. To elucidate the relationships among these parameters, two distinct models are required. One model captures the time course function of drug dosage to insulin concentration, while the other describes the relationship between insulin concentration and glucose concentration. This process is illustrated in Figure 3.5 The goal of the controller design is to minimize the error, ensuring that the output accurately tracks the desired blood glucose level. The controller achieves this by driving the pump to administer continuous insulin infusion. Prior to designing the controllers, it is essential to first model the plant.[13]

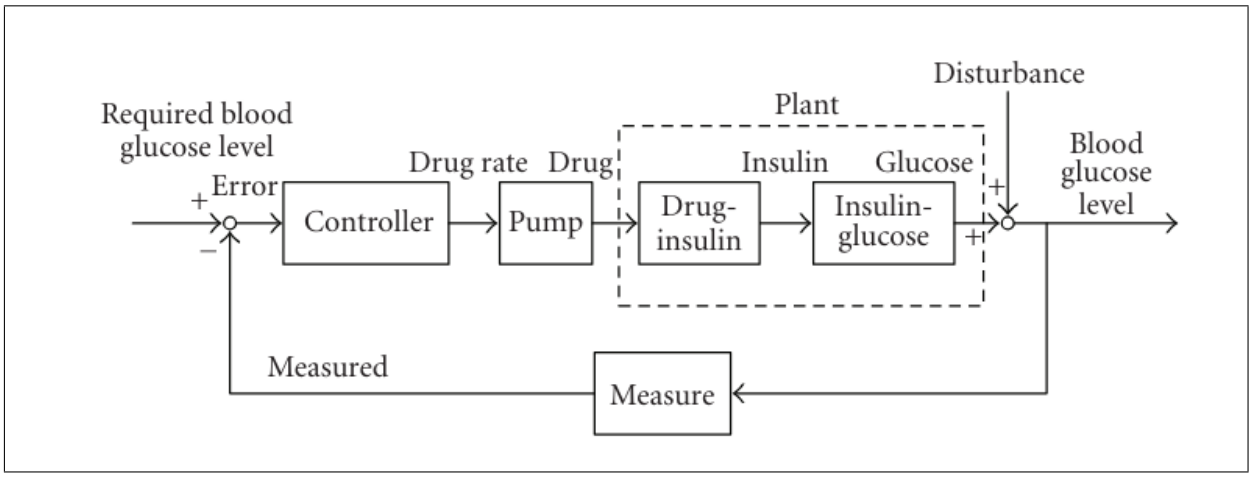


Figure 3.5: Closed-loop framework of blood glucose concentration control.

3.1 A continuous model of drug to insulin

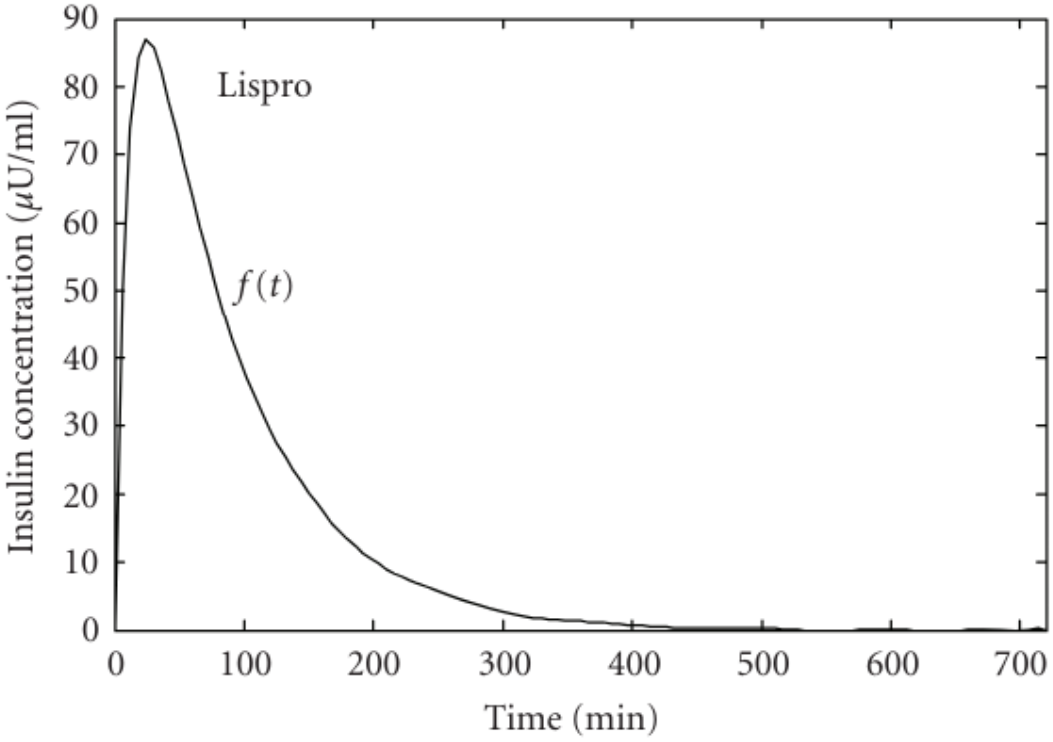


Figure 3.6: Time course of plasma insulin concentration after a subcutaneous injection (10 U) of Lispro.

The development of implantable sensor technology has enabled continuous insulin injection. . There have been a number of results regarding related topics[14]. Pharmaceutical research has produced various types of insulin, administered through combined and subcutaneous injections, to manage glucose levels. Fast-acting insulin preparations like Lispro and regular insulin, as well as slow-acting ones such as neutral protamine Hagedorn (NPH), are commonly used to meet basal insulin requirements. In this work, it is assumed that only Lispro is used to produce insulin[15], Figure 3.6 illustrates the plasma insulin concentration following a subcutaneous injection of a typical Lispro dose.

The function *f(t, d)* is defined to describe the time course of plasma insulin concentration after a subcutaneous injection, the function *f(t)* can be obtained with the curve described in Figure 3.7 The effects on insulin concentration each time should be cumulated. There-

fore, the integral form is used as follows to calculate the insulin concentration:

$$I(t) = \int_{t-360}^{t} d(\tau) \cdot f(t-\tau) d\tau \tag{3.1}$$

3.2 A continuous model of insulin to glucose

The relationship between insulin and glucose has been well investigated in recent years [16]-[17].

There are two primary proposed models for glucose and insulin dynamics: the Sorensen model and the minimal model.

The Sorensen model, a physiologically based compartmental model, is detailed in references, it is a six-compartment model representing the brain, heart and lungs, liver, gut, and kidney peripheral tissue. These compartments provide a physiological representation of glucose and insulin interactions within the body. [16]-[18]

Bergman model is widely used in the blood glucose-level control. It offers a good benchmark for testing the relationship between the insulin and the glucose. [18]-[17]

3.3 The Bergman model

It has long been hoped that our understanding of the Pathogenesis of diabetes would be helped by the use of mathematical modeling.

In 1979 Richard Bergman and Claudio Cobelli worked together to find a "minimal model" based upon experimental data from Bergman's laboratory. Model was chosen as the simplest representation based upon physiology known at the time. The model itself is two quasi-linear differential equations; one representing insulin kinetics in plasma, and a second representing the effects of insulin and glucose itself on restoration of the glucose after perturbation by intravenous injection.[19] The model can be depicted as follows:

$$\mathrm{G'(t)} = -\mathrm{p1} + \mathrm{X(t)G(t)} + \mathrm{p1\ Gb} + \mathrm{m(t)} \tag{3.2}$$

$$X'(t) = -p_2 X(t) + p_3 I(t) \tag{3.3}$$

$$I'(t) = \tau \cdot u(t) - n \cdot I(t) \tag{3.4}$$

Parameters	Value	Unit
p1	0.0337	min^{-1}
p2	0.0209	min^{-1}
n	0.214	min^{-1}
τ	5	min
Gb	0.811	*mg/mL*
M	0.012	*mg/mL/min*
G1	0.81	*mg/mL*
X1	0.0054	μ *U/mL*

Table 3.1: Parameter Values

In order to simplify the nonlinearity, the idea of linearity of Bergman model is proposed in [19]:

$$G'(t) = -[p_1 + X_1(t)]G(t) - G_1 \cdot X(t) + G_1 \cdot X_1 + p_1 G_b + m(t) \tag{3.5}$$

$$X'(t) = -p_2 X(t) + p_3 I(t) \tag{3.6}$$

$$I'(t) = \tau \cdot u(t) - n \cdot I(t) \tag{3.7}$$

With:
G(t) = the concentration of glucose
I(t) = the concentration of insulin
X(t) = the dynamic insulin response
Gb = the basal level of glucose
m(t) = the rate of exogenous glucose infusion
G1 = the average value of *G(t)*
X1 = the average value of *X(t)*
p1, p2, p3, τ and n are parameters defined in Table 1.

The above parameters in Bergman model can be obtained easily [20]-[21]

3.4 *PID* controller design for continuous closed-loop control system

There are numerous control and regulation algorithms available for real-world systems, ranging from simple proportional controls to highly sophisticated adaptive and predictive methods.

Despite these advanced techniques, the *PID* (Proportional-Integral-Derivative) controller has consistently shown optimized results and remains the most widely used and reliable solution.

A *PID* controller functions by calculating an error value as the difference between a desired setpoint and a measured process variable. It then applies corrections through three components: the proportional term addresses the current error, the integral term accounts for the accumulation of past errors, and the derivative term anticipates future errors based on their rate of change. This combination ensures precise and stable control in a wide range of applications.

The standard *PID* controller could be stated as:

$$\text{PID} = \frac{K_c \left(1 + \frac{s}{T_i}\right) (T_d s + 1)}{T_d \frac{s}{A_d} + 1} \tag{3.8}$$

with:

$Kc = P$

$Ti = I$

$Td = D$

$Ad = 10$

For this *PID* controller, there are three important parameters: *P, I* and *D*, where:

P is a proportional feedback in which the stronger it is, the more powerful the feedback is.

I is an integral role feedback, which benefits the steady performance but does not contribute to the dynamic performance of the system.

D is a differential role of feedback. Appropriate differential role of the plot can improve dynamic performance significantly.

The parameters are adjusted and chosen based on TRIAL and ERROR tuning method.

3.5 The Essence of the TRIAL and ERROR Method

The trial and error method is a heuristic technique that traditionally involves testing various possible solutions until one that succeeds is found. It is fundamentally driven by the action-feedback loop, where an action's outcome informs the next step. This method stands as a testament to the power of persistence, with its simplicity often masking its profound capacity to untangle complex problems. It is as though through repeated attempts and iterations, the layers of a problem are gradually peeled away, revealing the seed of a solution within. Historically, many of the greatest discoveries owe their existence to trial and error.

3.6 Closed-loop design

The insulin pump closed-loop control system consists of a *PID* controller, an insulin pump SIMSCAPE model, and two key blocks: the drug-to-insulin block and the insulin-to-glucose block. The system operates by using feedback to continuously adjust insulin delivery. The *PID* controller receives input from the glucose concentration feedback and compares it to a step reference, which represents the desired blood glucose level. Based on this comparison, the controller calculates the necessary adjustments and sends commands to the insulin pump. Which then administers the appropriate amount of insulin. The drug-to-insulin block models the conversion of administered insulin into plasma insulin concentration, while the insulin-to-glucose block represents the physiological response of blood glucose levels to insulin. This integrated approach ensures precise regulation of blood glucose levels, maintaining them within the desired range.

Additionally, the system accounts for disturbances such as meal-induced glucose fluctuations, ensuring precise and adaptive glucose regulation even in the presence of dietary variations.

About the drug-to-insulin model was represented by the function *f(t)*, in which it was possible to get it a mobile application.

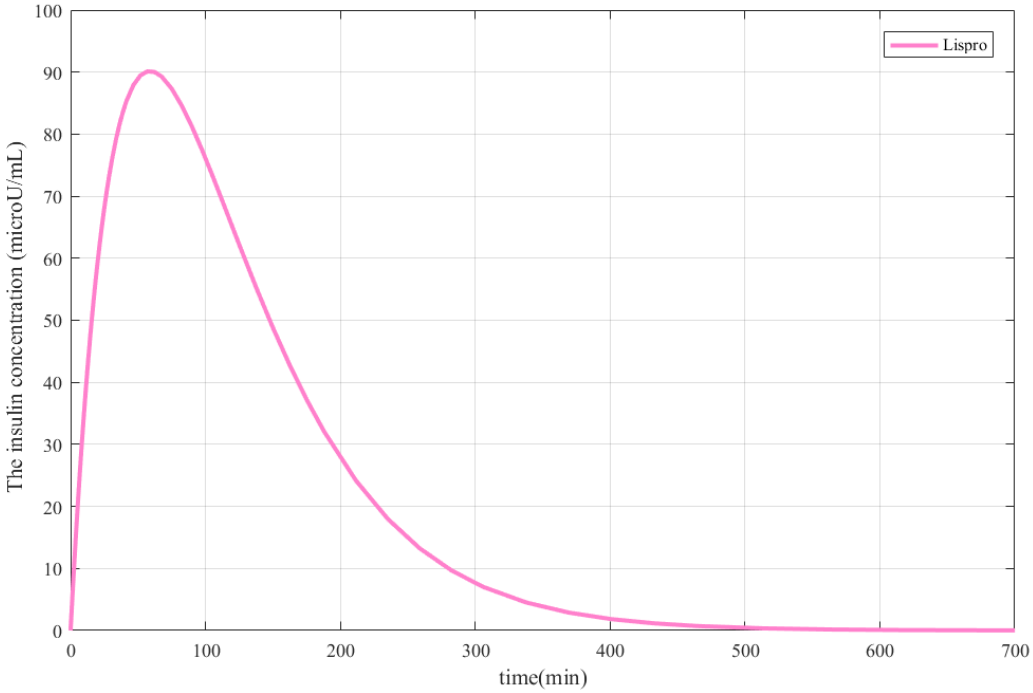


Figure 3.7: The Lispro *f(t)* function

For the model of insulin to glucose, LAPLACE transform is applied to (1), (2), and (3), the transfer function from insulin to glucose is presented with the parameters shown in Table 1, as follow:

$$G(s) = \frac{-0.00003}{s^3 + 0.274s^2 + 0.013656s + 0.00018} \tag{3.9}$$

The main disturbance caused by three meals can be depicted as a curve shown in figure 3.8. Under the disturbance, we want to design a controller to meet the requirements of normal person's glucose concentration of about 60–100 mg/dL before the meal and less than 140 mg/dL after meal. As the meal disturbance is much higher than normal glucose concentration level, it demands a controller with good performance of disturbance rejection.

Figure 3.8: The meal disturbance during a day

3.7 SIMULINK model

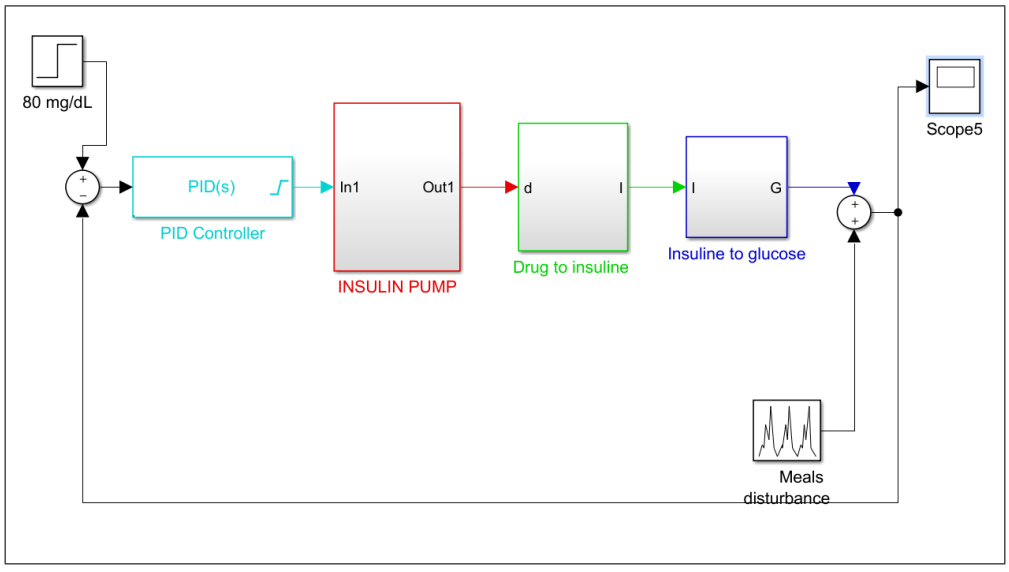
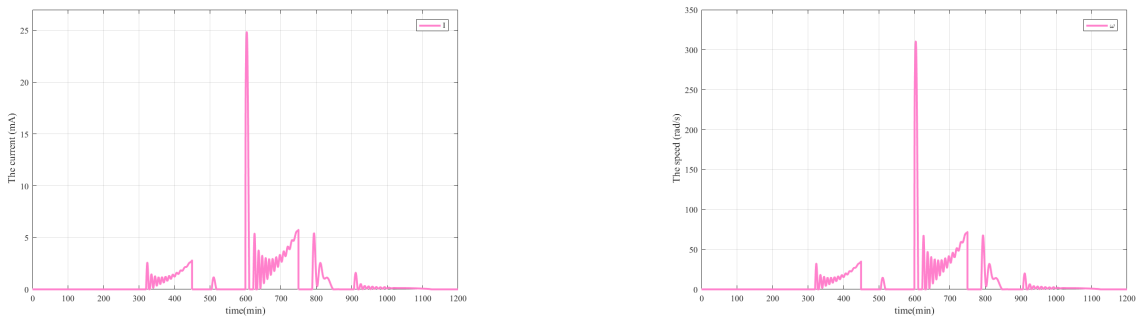


Figure 3.9: The SIMULINK closed-loop model

The figure 3.8 represents a part of the SIMULINK model.

- The cyan block represents the *PID* controller.
- The red block represents the insulin pump subsystem.
- The green block represents the function in which the Insulin quantity was obtained.
- The blue block illustrates the transfer function which is responsible of the translation from insulin to glucose and the relation between them (equation 3.7).

3.8 Simulation results



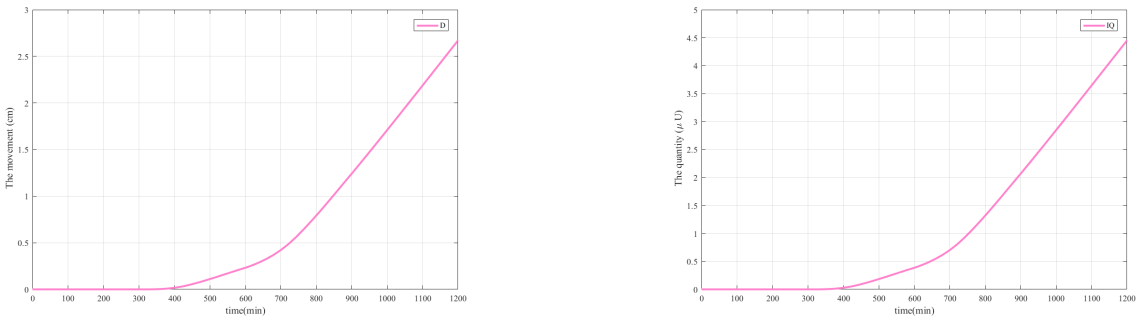
(a) The DC motor current curve **(b)** The DC motor speed curve

Figure 3.10: The DC motor electrical quantities graphs

These figures illustrate the performance of the DC motor within the insulin pump, The current starts at a low value, then increases rapidly, reaching a peak around 1500 minutes. After the peak, the current starts to decline, eventually dropping back to a low value. The current curve follows a similar pattern to the speed curve, with an initial ramp-up, a peak, and then a decline. The correlation between the speed and current graphs suggests that the DC motor's performance is being monitored and controlled within the insulin pump system. The peak in both the speed and current around 1500 minutes indicates a critical point in the motor's operation, which may be related to the insulin delivery requirements or the overall system's performance. It's also legit to say that these curves somehow follows the disturbance pattern which means that the rising of the external glucose level requires higher motor speed.

PID limitation technique

To ensure that the DC motor only rotates in the positive direction, It's effective to use the limitation strategy on the output signal. Specifically, constraining the *PID* controller's output to a minimum value of zero, effectively preventing the motor from receiving any command that would induce a negative rotation. By doing this, any corrective action taken by the *PID* controller, whether proportional, integral, or derivative, is restricted to non-negative values, thereby ensuring that the motor maintains its positive rotational direction and eliminating the possibility of reversing.



(a) The lead-screw nut movement variation **(b)** The insulin quantity variation

Figure 3.11: The nut movement and the insulin quantity curves

The figure shows both nut movement and insulin quantity variation, As it's quite obvious that the two curves have the same shape, and that indicates the continuous increase of the nut translational movement and the insulin delivery.

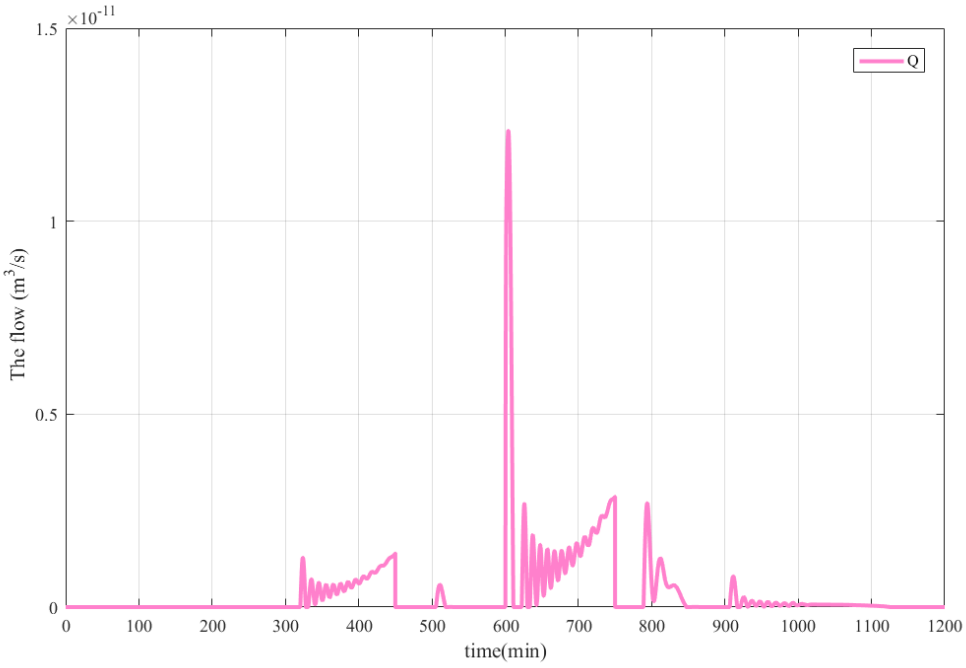


Figure 3.12: The insulin flow curve

Before obtaining the insulin quantity, the insulin-pump output was about a flow, running from the piston-cylinder terminal as it also follows the speed pattern which means whenever the DC motor rotation increases it provokes higher insulin flow.

3.9 The glucose level simulation results

The whole system output is about the patient glucose level after during the continuous injection, the figure below shows how the *PID* works on regulating this level in the diabetic body:

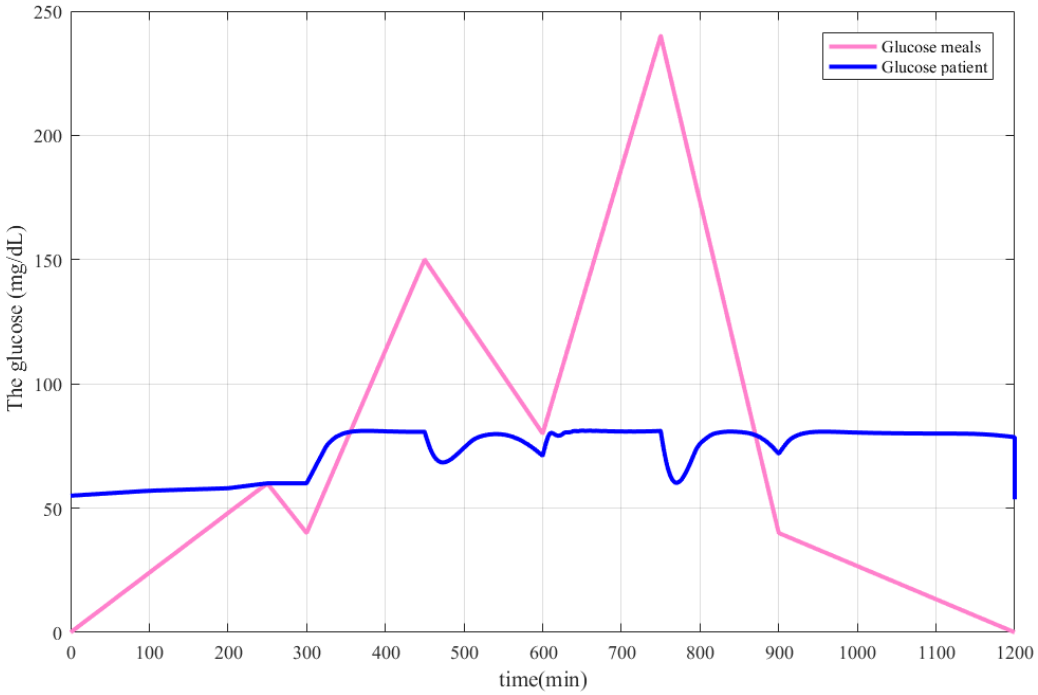


Figure 3.13: The patient blood sugar level compared to the external disturbance glucose level

This figure reflects the maintained glucose level within the desired range throughout the entire duration. As it shows consistent glucose concentration, starting from zero at the motor start and remaining within the target range $[60\,(mg/dL)\ 100\,(mg/d)]$ without significant fluctuations. The curve indicates that the tuning of the parameters P, I, and D, has been successful in effectively regulating the output. The consistent glucose level suggest that the insulin pump system is accurately delivering insulin to maintain the blood sugar within the desired range, demonstrating an optimal control.

Overall, this graph signifies the effectiveness of the final tuning in achieving the desired outcome of stable and well-controlled blood glucose levels, reflecting an ideal scenario for managing diabetes through the use of a controlled insulin pump with *PID*.

It depicts carefully the impact of a glucose management device on blood sugar regulation for the patient, when the striking difference between the two curves highlights the effectiveness of the glucose management device in improving glucose control in the ill body, by minimizing the glucose disturbances,and managing the patient's diabetes or other glucose regulation issues.

4 Closed-Loop vs. Open-Loop Insulin Delivery

Open-loop

Open-loop insulin delivery systems require the user to manually monitor their glucose levels and determine appropriate insulin doses. This offers a simpler, more user-controlled approach, but requires constant vigilance and decision-making from the individual. Open-loop systems are less responsive to immediate changes in blood glucose, as the user must recognize the need for an adjustment and input the new insulin dose. This can lead to greater glycemic variability and a higher risk of hypo- or hyperglycemic events. The trade-off for open-loop systems is simplicity and user autonomy, at the expense of the precision and automation provided by closed-loop technology.

Closed-loop

In contrast closed-loop insulin delivery systems offer significant advantages over traditional open-loop systems. These systems utilize continuous glucose monitoring (CGM) to automatically and continuously track a person's blood glucose levels. Based on the real-time glucose data, the system's control algorithm automatically calculates and delivers the appropriate insulin dosage, adjusting it as needed. This closed-loop approach provides more precise and stable glucose control, helping to minimize potentially dangerous blood sugar fluctuations. By automating insulin delivery, closed-loop systems require less hands-on management from the user, reducing the burden of constant monitoring and manual adjustments. This can lead to better glycemic outcomes and improved quality of life for people with diabetes.

The key advantage of closed-loop systems is their ability to rapidly respond to changes in glucose levels. Rather than waiting for the user to recognize a change and manually intervene, the automated system can quickly detect a rise or drop in blood sugar and adjust insulin delivery accordingly. This helps avoid dangerous high or low blood glucose episodes that can occur with open-loop management. The improved glucose stability and reduced risk of complications are significant benefits of closed-loop technology.

However, closed-loop systems do come at a higher cost and complexity compared to open-loop insulin pumps. The additional CGM hardware and sophisticated control algorithms add to the overall system expense. Additionally, users must be comfortable relying on

the automated insulin delivery and be diligent about calibrating the CGM sensor. But for many, the advantages of tighter, more responsive glucose control outweigh these drawbacks.

5 Conclusion

Now that the last part of this work is done, it's legit to mention that the desired and optimal result was successfully obtained, for the case of open-loop model it was possible to adjust the performance as required with no feedback even though similar or better results can be obtained following an advanced technique or even artificial intelligence . The closed-loop scenario needed the integration of *PID* controller to the insulin pump, beside modeling the human body by extracting the relation between the insulin and glucose in there, in the end it was possible to control a whole closed loop system in order to visualize the desired output represented by the blood glucose level.

General conclusion

General conclusion

This thesis aimed to model and control an insulin pump, a groundbreaking invention in medical history essential for diabetes management. The goal was to create a comprehensive model representing the pump's operational dynamics and design a control system to optimize its performance. Enhancing the modeling and control mechanisms of insulin pumps can improve their efficacy, reliability, and user-friendliness, thereby contributing to better patient outcomes and quality of life for individuals with diabetes. This research endeavors to advance medical technology and lay a foundation for future innovations in insulin pump design and functionality.

The first chapter provides a comprehensive overview of diabetes and insulin pumps. It discusses the different types of diabetes, their causes, symptoms, and treatment options, and traces the history and evolution of insulin therapy. By highlighting advancements in insulin pump technology, this chapter underscores the significance of these devices in managing diabetes and improving patients' quality of life. This foundational knowledge sets the stage for the detailed discussions and analyses in the subsequent chapters.

Building on this foundational knowledge, the second chapter focuses on modeling the insulin pump. It develops mathematical models for each component DC motor, speed reducer, screw-nut mechanism, and piston-cylinder assembly—based on governing physical laws. These models are explained briefly, and their equivalent SIMSCAPE models are created to provide accurate simulations. This detailed modeling lays the groundwork for the control strategies discussed in the following sections, ensuring a precise representation of the pump's operational dynamics.

The third chapter, it was legit to illustrate the behavior of the pump under plenty of circumstances and changes, starting by visualising the device performance under open-loop

standards, the result were successfully obtained, when it comes to the closed-loop model, *(PID)* implementation helped the fine tuning of the system.

Bibliography

[1] National Institute of Diabetes and Digestive and Kidney Diseases. What is diabetes?, May 2024.

[2] Diabetes: Symptoms and causes, 2024.

[3] Nuha A. ElSayed, John B. Buse, Torsten J. Jakobsen, and Melanie J. Davies. 2. classification and diagnosis of diabetes: Standards of care in diabetes–2023. *Diabetes Care*, 46(Suppl 1):S19–S40, Dec 2022.

[4] Brenda I. de Cortez, Martha Isela Cortez, Juan Miguel, and Mónica Espinoza Rojo. Insulin: A connection between pancreatic cells and the hypothalamus. *World Journal of Diabetes*, 14(2):76–91, Feb 2023.

[5] Wikipedia contributors. Insulin pump, Mar 2006.

[6] Karen M. Bolderan. Insulin pump therapy advantages and disadvantages, 2013.

[7] Michael Dansinger. What are insulin pumps?, Nov 2022.

[8] Salah I.S. Tnatin, Seliman A. Mohamed, and Fatma R.M. Abdallati. Experimental and simulation study of a permanent magnet d.c. motor at steady state. *AL-MUKHTAR JOURNAL OF ENGINEERING RESEARCH*, Sep 2017.

[9] Bin Yao and John Bystrom. *Design and Control of Precision Actuators for Medical Applications*. Springer, 2015.

[10] Miles Budimir. Guide on encoders: Deep dive on incremental and absolute encoders, 2021.

[11] Kripa Varanasi and Samir Nayfeh. The dynamics of lead-screw drives: Low-order modeling and experiments. *Journal of Dynamic Systems Measurement and Control*, 126, Jun 2004.

[12] Andrew Parr. *Hydraulics and Pneumatics: A technician's and engineer's guide*. Elsevier Science, 2013.

[13] Jiming Chen, Kejie Cao, Youxian Sun, Yang Xiao, and Xu (Kevin) Su. Continuous drug infusion for diabetes therapy: A closed-loop control system design. *EURASIP Journal on Wireless Communications and Networking*, 2008(1):495185, 2007.

[14] M. Mahfouf, A.J. Asbury, and D.A. Linkens. Unconstrained and constrained generalised predictive control of depth of anaesthesia during surgery. *Control Engineering Practice*, 11(12):1501–1515, 2003. Award winning applications-2002 IFAC World Congress.

[15] R.S. Parker, E.P. Gatzke, and F.J. Doyle. Advanced model predictive control (mpc) for type i diabetic patient blood glucose control. In *Proceedings of the 2000 American Control Conference. ACC (IEEE Cat. No.00CH36334)*, volume 5, pages 3483–3487, 2000.

[16] K.H. Kienitz and T. Yoneyama. A robust controller for insulin pumps based on h-infinity theory. *IEEE Transactions on Biomedical Engineering*, 40(11):1133–1137, 1993.

[17] N. Ghevondian and Hung Nguyen. Using fuzzy logic reasoning for monitoring hypoglycaemia in diabetic patients. In *Proceedings of the 19th Annual International Conference of the IEEE Engineering in Medicine and Biology Society. 'Magnificent Milestones and Emerging Opportunities in Medical Engineering' (Cat. No.97CH36136)*, volume 3, pages 1108–1111, 1997.

[18] Fidimahery Andrianasy and Maurice Milgram. Applying neural networks to adjust insulin-pump doses. *Neural Networks for Signal Processing VII. Proceedings of the 1997 IEEE Signal Processing Society Workshop*, pages 182–188, 1997.

[19] R.N. Bergman. Origins and history of the minimal model of glucose regulation. *Front Endocrinol (Lausanne)*, 11:583016, Feb 2021.

[20] F. Chee, A.V. Savkin, T.L. Fernando, and S. Nahavandi. Optimal h insulin injection control for blood glucose regulation in diabetic patients. *IEEE Transactions on Biomedical Engineering*, 52(10):1625–1631, Oct 2005.

[21] C. Ionescu, S. Zlate, and R. De Keyser. An approach to control the blood glucose level in diabetic patients. In *2006 IEEE International Conference on Automation, Quality and Testing, Robotics*, volume 1, pages 48–53, 2006.