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THESIS

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Field: Electrotechnics
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THEME

PLANAR MAGNETIC BEARING CONTROL

Presented and evaluated, the 11/ 06 /25 , by the jury composed of:

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Abstract

Magnetic bearings are innovative devices that support a rotating shaft without physical contact by using magnetic forces to suspend it in space. Among them, planar magnetic bearings are particularly important in applications that demand high precision, zero wear, and operation in extreme environments such as vacuum, high speed, or contamination-sensitive conditions

Unlike passive bearings that rely solely on permanent magnets, Active Magnetic Bearings (AMBs) use electromagnets controlled by digital feedback systems. This allows real-time control of rotor position and dynamic adjustment of system parameters such as stiffness and damping without mechanical intervention . Such adaptability is especially valuable in high-performance fields like gas turbines, cryogenic systems, and aerospace applications .

In planar magnetic bearings, suspension in two dimensions (typically within the horizontal plane) presents additional control challenges to maintain system stability. Traditional control approaches such as PID controllers are widely used but can struggle with the system's nonlinearities. Therefore, intelligent control methods, such as fuzzy logic controllers, are increasingly adopted to enhance robustness and overall system performance .

The main advantages of planar magnetic bearings include:
- Frictionless operation, leading to no mechanical wear,
- High precision in shaft positioning,
- Suitability for harsh or vacuum environments,
- Significant long-term maintenance cost savings .

In summary, planar magnetic bearings represent an advanced and highly reliable solution for demanding applications where cleanliness, precision, and efficiency are critical.

Keywords :

Magnetic bearings -levitation -train- maglev- German Trans-rapid-electromagnetic -PID correction- stability -pole placement method-control – fuzzy logic

Résumé

Les **paliers magnétiques plans** permettent de supporter un arbre en rotation sans contact mécanique, grâce à des forces magnétiques. Ils sont particulièrement adaptés aux environnements exigeants nécessitant une haute précision, une absence d'usure, et un fonctionnement propre, comme les systèmes sous vide, les machines à grande vitesse ou les applications spatiales.

Contrairement aux paliers passifs, les **paliers magnétiques actifs (AMBs)** utilisent des électroaimants contrôlés par des systèmes numériques, permettant une régulation dynamique de la position du rotor, de la raideur et de l'amortissement. Cette capacité de contrôle en temps réel est essentielle pour garantir stabilité et performance dans des conditions extrêmes.

Cependant, le contrôle des paliers magnétiques plans en deux dimensions introduit des défis supplémentaires, notamment en raison des non-linéarités du système. Si les contrôleurs PID sont largement utilisés, leur efficacité peut être limitée. C'est pourquoi des approches plus avancées, telles que les **contrôleurs à logique floue**, sont de plus en plus adoptées pour améliorer la robustesse et la performance globale.

Les principaux avantages de cette technologie incluent l'absence de frottement, une grande précision, une compatibilité avec des environnements sévères, et une réduction significative des coûts de maintenance.

Mots – clés :

Paliers magnétiques-Lévitation-Train-Maglev-Transrapid allemand-Électromagnétique-Correction PID-Stabilité-Méthode de placement de pôles-Commande -Logique floue

ملخص

تُستخدم الحمولات المغناطيسية المستوية لدعم عمود دوّار دون تلامس ميكانيكي، وذلك بالاعتماد على قوى مغناطيسية تُولّد حالة من التعليق أو الرفع. وتتميّز هذه التقنية بكونها مثالية للبيئات الدقيقة والمتطلبة التي تحتاج إلى دقة عالية، وغياب الاحتكاك والتآكل، وتشغيل نظيف، مثل أنظمة الفراغ، والآلات ذات السرعة العالية، والتطبيقات الفضائية.

وعلى خلاف الحوامل الساكنة (التمغنطية السلبية)، تعتمد الأنظمة المغناطيسية الفعالة على مغانط كهربائية يتم التحكم بها بواسطة أنظمة رقمية، مما يتيح تنظيمًا ديناميكيًا فوريًا لموضع الدوّار، وقساوته، ومعدل التخميد فيه. وتُعد هذه القدرة على التحكم اللحظي أمرًا حاسمًا لتحقيق الاستقرار والأداء الفعّال في ظروف تشغيلية قاسية.

غير أن التحكم في الحوامل المغناطيسية ثنائية الأبعاد يفرض تحديات إضافية، لا سيما بسبب اللاخطية المتأصلة في النظام. ورغم أن أنظمة التحكم PID تُستخدم على نطاق واسع لبساطتها، إلا أن فعاليتها تبقى محدودة في مثل هذه الحالات، مما دفع إلى تبنّي تقنيات أكثر تقدمًا، مثل المنطق الضبابي، التي توفّر مرونة أعلى وأداءً أفضل في مواجهة التغيرات والاضطرابات.

:وتكمن أهم مزايا هذه التكنولوجيا في ما يلي

-انعدام الاحتكاك الميكانيكي

-دقة عالية في تحديد الموضع،.

-ملاءمة للبيئات القاسية.

–انخفاض كبير في تكاليف .
-الصيانة والتشغيل.

الكلمات المفتاحية

المحامل المغناطيسية - الرفع - القطار - ماجليف – القطار ألماني السريع - كهرومغناطيسي - تصحيح- - المنطق الضبابي المغناطيسي. التحكم بPID-الاستقرار

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Dedication

Alhamdulillah , who bring us there in this point of success and who doesn't thank people doesn't thank god so :

I dedicate all my efforts in this work to the soul of my dear ***FATHER****. To the memory of my beloved dad—your wisdom, strength, and quiet encouragement continue to guide me, even in your absence. Though you are no longer here to witness this milestone, your influence is present in every step I take. This work stands as a tribute to the values you instilled in me and the dreams you helped me believe in. You are deeply missed and forever remembered.*

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Table of contents

Nomenclature i

List of Figures.....ii

List of Tables.....iii

General introduction 01

Chapter I :Generalities of planar magnetic bearings

I-1Introduction …….....……04

I-2 Earnshow's theorem …….....…….……04

I-3 Different type of magnetic bearings …….....……..…..04

I-3-1 passive magnetic bearings (PMB)…….....……..…..04

I-3-2 Permanent magnet bearings…….....…….04

a. Axial permanent magnet bearing structure …….....……....05
b. Radial permanent magnet bearing structure …….....……..05

I-3-3 Variable reluctance bearings …….....……...05

I-3-4 Characteristics of the passive magnetic bearings …….....……...06

I -3-5 Active magnetic bearings (AMB)…….....…….06

-The active magnetic bearings of the future …….....……...06

I -3-6 Hybrid magnetic bearing (HMB)…….....…….07

I-4 Domain of application …….....……...08

I-4-1 Machine tools …….....…….08

I-4-2 Medical devices …….....……..08

I-4-3 Turbo machinery ……..…….....……08

I-4-4 Magnetic trains ……..…...……09

a-Maglev …….…….....……..09

b-The German trans-rapid …….....…….....……..11

I-6 Conclusion …….…...…….12

Chapter II: Planar magnetic bearings control technics

Introduction 14

II.2 Control technics 14

II.2.1 Enslaved system correction …….....……15

II.2.1.1 Proportional correction P……...……..…...15

II.2.1.2 Integral correction I ……...……..……16

II.2.1.3 Derivative correction D ……...…….…...17

II.2.1.4 Integral proportional correction PI ……...…….....…18

II.2.1.5 Derivative proportional correction PD ……....…….……..19

II.2.1.6 The PID corrector ……...…….……20

II.2.1.7 Practical determination of the parameters of a corrector……..…....…….21

II.2.2 Stability study ……..……..21

II.2.2.1 Definition of the location of the poles (root locus)……....…..……21

II.2.3 Correction by Fuzzy logic (Fuzzy control)……...……..22

II.2.3.1 Applications of Fuzzy logic in wireless communications ……...…...23

II.2.3.2 Advantages and disadvantages of using Fuzzy logic in

these application ……..……....24

a. Advantages …….……24
b. Disadvantages ....……..……...24

II.4 Conclusion …….…….. 25

Chapter III: Analytical Modeling of the Planar Bearing

Introduction ……..……..……..…27

III.2 Analytical modeling ……..……..……..…27

III.2.1 Magnetic force model ……...……...……27

III.2.2 Newton's low (Dynamic equation)…….....……28

III.2.3 Transfer function ……...……..……28

III.2.4 Control by pole placement method for the system …….....……..29

III.2.4.1 PID controller ……...……..……..29

III.2.4.2 PD controller ……..…..……....30

III.3 Fuzzy control method …….…...……....31

III.4 Conclusion ……..……..34

Chapter IV: Control of a Planar Magnetic Bearing

IV.1 Introduction……...……....36

IV.2 Control by a PID controller ……..…...…….....36

IV.3 Control by a PD controller…….……....….....39

IV.4 Control by a Fuzzy controller…….....41

- Remark…….…….....41

IV.4.1 Diagram under MATLAB (Simulink)…….……...….....41

IV.4.2 The operation of a fuzzy controller……..……..…….....……..42

- Linguistic variables……..…….....42
- Membership functions…….……..…….....43
- Rules of inference…….…….....45
- simulation results……..…….....47

IV.5 the comparison between Controllers (PID,PD,Fuzzy logic)…….……....…….....49

IV.5.1 the result …….……..…….....49

IV.6 Conclusion…….…….....50

General conclusion.....52

Bibliographic references 54

Nomenclature

Greek symbols

Δ:derivative of u

ρ:poles

∂:derivative of F

Cyrillic symbols

ε: the output of the system

Indices

x:position

i:input or current

x_{ref} :reference position

PID: proportional-integral-derivative controller

P:proportional controller

I:integral controller

D:derivative controller

Abbreviations

AMB :active magnetic bearing

PMB: passive magnetic bearing

PID: proportional-integral-derivative controller

Ns:small negative

Nm:medium negative

Nb:big negative

Z:zero

Ps:small positive

Pm:medium positive

Pb:big positive

Figures list

Fig1.01: The two basic structures of permanent magnet bearings.....05
Fig1.02:variable reluctance bearings.....06
Fig1.03: Maglev levitation.....10
Fig1.04: Allemand trans-rapid.....11
Fig2.01:overall structure of system 15
Fig2.02:overall structure and result of a P corrector.....16
Fig2.03:overall structure and result of a I corrector 17
Fig2.04:overall structure and result of a D corrector 18
Fig2.05:overall structure and result of a PI corrector 19
Fig2.06:overall structure and result of a PD corrector 20
Fig2.07:overall structure and result of a PID corrector Control by fuzzy controller.....23
Fig2.08: Structure of a Fuzzy Logic Controller.....24
Fig3.01: Pole Zone for Stable Response in a Third-Order System.....29
Fig3.02: Pole Zone for Stable Response in a second-Order System.....30
Fig4.01: Matlab simulink of control by a PID controller.....36
Fig4.02: System response for a desired position of 5×10^{-3}m by PID controller.....37
Fig4.03: The electromagnetic force of the system.....38
Fig4.04: The error between the reference position and the estimated.....38
Fig4.05: MATLAB Simulink of control by a PD controller.....39
Fig4.06: System response for a desired position of 5×10^{-3}m by PD controller.....40
Fig4.07: The electromagnetic force of the system of control by a PD controller.....40
Fig4.08: The error between the reference position and the estimated by PD controller.....41
Fig4.09: MATLAB Simulink of control by a Fuzzy controller.....42
Fig4.10: Fuzzy regulator.....42
Fig4.11: Fuzzy logic designer.....43
Fig4.12(a): Membership function 'error'.....44
Fig4.12(b): Membership function 'error's derivative'.....44
Fig4.12(c): Membership function 'command'.....45
Fig4.13: Implementation of rules in the Matlab (fuzzy controller) 46
Fig4.14: Graphical representation of the rules.....46

Fig4.15: System response for a desired position of 5×10^{-3}m by Fuzzy controller.....47
Fig4.16: The electromagnetic force of the system of control by a Fuzzy controller.....48
Fig4.17: The error between the reference position and the estimated by Fuzzy controller.....48
Fig4.18:the simulation of the comparison between controllers.....49
Fig4.19: the result of comparison.....50

Table List

Table01:conditions of fuzzy control.....33

General Introduction

Magnetic bearing control remains a critical area of research and development, enabling high-speed, contact-free rotational systems used across aerospace, energy, and precision engineering sectors. The inherent instability and nonlinear dynamics of Active Magnetic Bearings (AMBs) have driven the need for increasingly sophisticated control algorithms. While early strategies such as PID controllers offered basic closed-loop stability, they lacked robustness against external disturbances and model uncertainties. In contrast, advanced control approaches including H∞ control, μ-synthesis, nonlinear feedback linearization, adaptive control, and Model Predictive Control have significantly enhanced performance. These modern methods enable precise rotor positioning, vibration suppression, and energy-efficient operation.

Additionally, state-of-the-art research emphasizes the importance of real-time implementation, sensor less estimation, and fault-tolerant design, which are increasingly crucial for industrial viability. The integration of artificial intelligence and advanced computational tools is opening new paths toward predictive maintenance, self-optimizing controllers, and intelligent fault detection. As a result, the field is steadily progressing toward resilient, low-power, and adaptive magnetic bearing systems capable of operating reliably in dynamic or extreme environments.

Magnetic levitation systems, which suspend objects without physical contact using magnetic forces to counteract gravity, are open-loop unstable by nature. This instability arises because magnetic force is nonlinear and inversely proportional to the square of the air gap between the magnet and the levitated object. Without feedback control, even small deviations from equilibrium can lead to system collapse or pull-in.

Compared to Passive Magnetic Bearings (PMBs) which rely solely on static forces from permanent magnets AMBs are preferred due to their superior dynamic controllability and precision. They can be used in harsh or vacuum environments, and their active electromagnetic components allow for accurate shaft positioning, integration with process automation, and adaptive control of stiffness and damping. Another major benefit is the elimination of lubrication systems, leading to reduced maintenance and cost savings.

In control design, PID components serve key functions: the proportional action enhances responsiveness; the integral action improves steady-state accuracy; and the derivative action contributes to stability. A PI controller offers improved accuracy without significantly affecting

stability. However, integral and derivative terms must be used cautiously especially in time-varying frequency environments as they can destabilize the system if improperly configured.

Furthermore, a PD controller is non-causal and cannot be physically realized using standard operational amplifiers. It also provides ineffective when error variation is slow, limiting its usefulness in some applications.

Chapter I:

Generalities of planar magnetic bearings.

Ⅰ -1 Introduction

This first chapter introduces the basic concepts related to **planar bearings**, which are crucial components in many mechanical systems used to support and guide loads in specific directions. These bearings typically operate using a thin film of fluid to minimize friction and wear between two surfaces in relative motion.

We begin by presenting **Earnshaw's Theorem**, a fundamental theoretical result that explains the limitations of static stability in systems governed by electrostatic or magnetic forces. Although originally formulated for electrostatics, the theorem also has broader implications in understanding non-contact bearing systems.

Next, we explore the **different types of planar bearings**, highlighting their geometric configurations, operating principles, and typical usage conditions.

Finally, we conclude the chapter with an overview of the **application domains** of planar bearings, showcasing their use in precision engineering, aerospace systems, machine tools, and micro-positioning devices.

This chapter lays the essential groundwork for understanding the physical and technical principles behind the design and operation of planar bearings.

Ⅰ -2 Earnshow's theorem

In 1839, Samuel Earnshaw presented a paper to the Cambridge Philosophical Society, in which he showed that it is impossible to place a collection of bodies, subject only to electrostatic forces, in such a way that they remain in a stable equilibrium configuration. This is now known as Earnshaw's Theorem.[6]

Ⅰ-3 Different type of magnetic bearings

Ⅰ-3-1 passive magnetic bearings (PMB)

Passive magnetic bearings are the easiest to make. They are self-driving, and their operations do not need no electricity supply from outside or cooling. Rephrase However, they cannot be used solely for stability reasons (according to Earnshaw's theorem). They must be connected with a mechanical device or mixed with other magnetic bearing systems.

- **Permanent magnet bearings.**
- **Variable reluctance bearings.**

Ⅰ-3-2 Permanent magnet bearings

Permanent magnet bearings mainly maintain the relative spatial position of the stator and rotor through the attractive or repulsive force generated by the interaction of the permanent magnets made of NdFeB materials. The structure of the suction permanent magnet bearing is composed of two basic forms: [7]

a. Axial permanent magnet bearing structure

How it works:

- ✓ Magnets are placed above and below the shaft.
- ✓ The restoring forces (shown by vertical arrows) pull or push the rotor back into position if it moves vertically.

b. Radial permanent magnet bearing structure

How it works:

- ✓ Permanent magnets are placed around the sides of the shaft.
- ✓ The restoring force (shown by horizontal arrows) acts inward when the shaft moves off-center.
- ✓ This keeps the rotor centered radially. [8]

✓

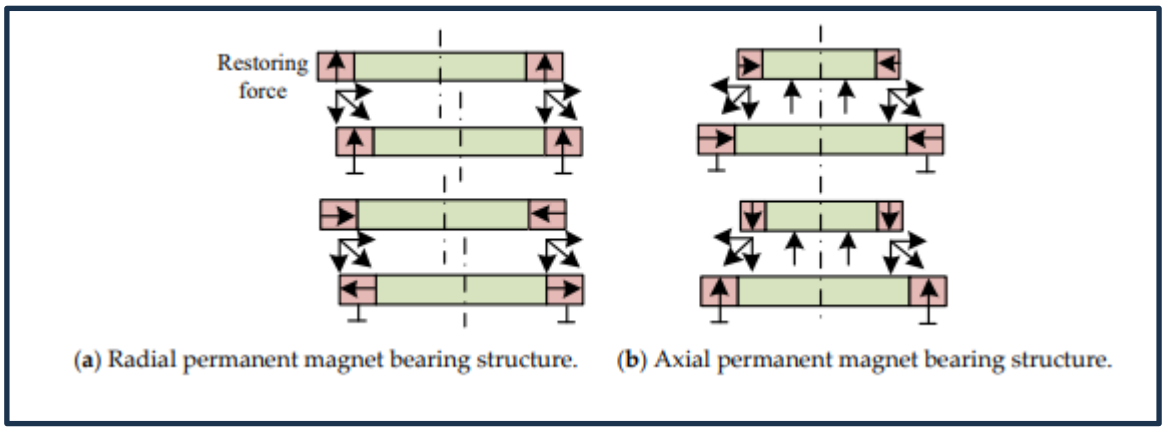


Fig1.01 : The two basic structures of permanent magnet bearings. [8]

I -3-3 Variable reluctance bearings

The operation of the bearings is not based on the principle of direct interaction between magnets, they are composed of two independent magnetic circuits, one of which is connected to the movable part while the other is connected to the fixed part.

the magnetic circuits are composed of two teeth opposite each other, half of these teeth is placed on the static part of the bearing, while the other on the movable part of the bearing, a difference in magnetic potential is created between these teeth either by a coil,

by a magnet, this difference in magnetic potential creates a flow which circulates between the teeth, This flow generates a pressure which tends to bring the teeth closer together. an elongation of the field lines and therefore a variation in the energy of the system, the teeth then seek to realign it in order to minimize this energy. The levitation is thus generated by the vertical variation of the system's reluctance.[9]

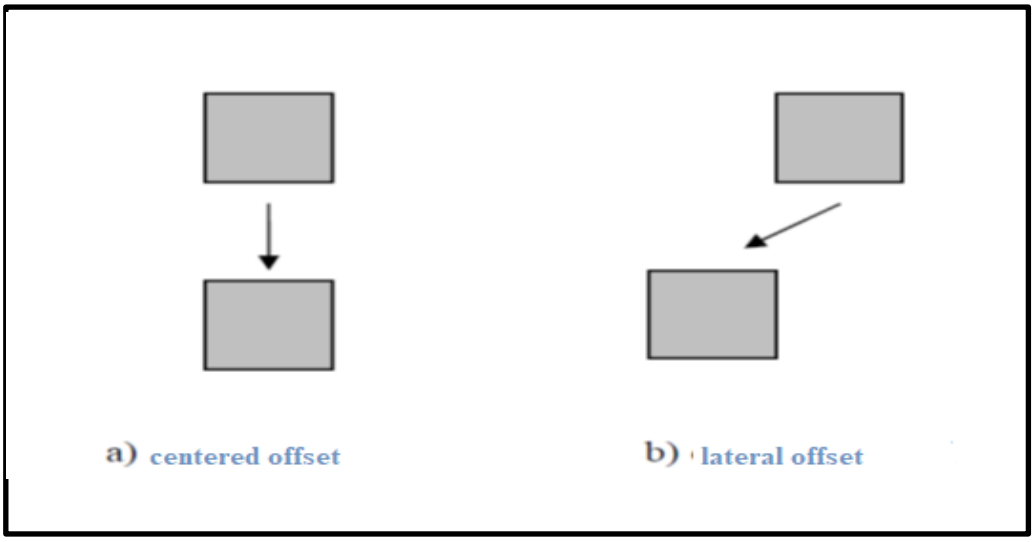


Fig1.02:variable reluctance bearings**.** [8]

I -3-4 Characteristics of the passive magnetic bearings

High speed rotating machines operating in harsh environments require PMBs that are reliable, cost effective and have a long operating life. They do not need a lubricant to operate effectively and can also be used in conjunction with active electromagnetic dampers to limit the unbalance response, stabilize rotor dynamic modes and lessen housing vibrations and rotational energy dissipation.[10]

I -3-5 Active magnetic bearings (AMB)

Active magnetic bearings levitate the rotational part of the electric motor using electromagnetic forces. By levitating the rotor there is no metal-to-metal contact between the rotating and stationary parts. This significantly increases energy efficiency and reduces the maintenance costs of high-speed motors. The need for high shaft speed is one of the factors that call for magnetic bearing over more traditional bearing types. [11]

-The active magnetic bearings of the future

Industrial electric motors are the largest end users of electricity. There are about 8 billion electric motors in the European union, consuming around half of the electricity EU produces. The existing solutions for high-speed electric motors are inefficient and expensive to maintain. More than 70% of their total lifecycle costs are for electricity and maintenance.

Active magnetic bearings (AMBs) are the solution to this problem. Industrial electric motors operate at high speeds (over 10,000 rpm). As a result, they are often subject to

failures and breakdowns that can affect the productivity and efficiency of the entire system they drive.

High-speed electric motors with magnetic bearings are attracting more and more attention in a wide range of industrial sectors. The motivation for using them varies considerably:

- The need for efficiency improvements and hence energy savings and environmental reductions.
- Power density enhancement, improved functionality, reliability and maintainability are some of the key drivers.

However, in the context of new and more demanding industrial applications, ranging from distributed power generation and energy storage to electric vehicles and industrial manufacturing processes, high-speed motors still face a number of challenges. [12].

I -3-6 Hybrid magnetic bearing (HMB)

Hybrid magnetic bearings operate on the same concept as active magnetic bearings, which me ans that in order to give the bearing rigidity and to reposition the rotor in the case of movemen t, a direct current (and hence a continuous flow) must be applied.
The distinction is that a permanent magnet, rather than a power current, is used to create the p ower flow in this instance.

I -4 Domain of application

The various advantages of the magnetic bearing have led to applications mainly in the five following areas:

I -4-1 Vacuum and cleanroom systems:

The bearings will not suffer from any mechanical wear or give rise to any related contamination, and if necessary, the bearings can even be arranged outside the vacuum container with field forces acting through the container walls. The absence of aerodynamic drag loses and the low energy consumption of the bearings is a welcome feature for flywheels for energy storage.

I -4-2 Machine tools:

A main advantage is the high precision that can be attained and the high rotational speed with relatively high load capacity. This is useful for heavy-duty high-speed milling of aluminum. The high speed is an essential requirement in the precision grinding of small parts.

I -4-3 Medical devices

A specific application is the use of magnetic bearings in an artificial heart pump, or more precisely, in a left ventricular assist device intended to assist an ailing heart in keeping the pumped blood at a desired rate, which is needed to provide the circulatory requirements.

I -4-4 Turbo-machinery:

Actually, the main application is of AMB is turb machinery. The area covers small turbo-molecular pumps up to turbo generators and compressors in the Megawatt range Turbo-generators in the 300 MW range are in an early planning stage already. An advantage is the possibility of controlling and damping vibrations, and obtaining a well-defined dynamic behavior. Furthermore, is possible to simplify machine construction, as there are no bearing fluids, usually oil, that have to be kept away from the process fluid by seals. Other important features that have been corroborated by practical experience sue the inherent means for self-control and diagnosis the very low maintenance costs, and the low energy.

I -4-5 Magnetic levitation trains:

Designing this train is centered around controlling the height at which it is levitating. More specifically, in order to ensure safe operation, the distance between the magnet attached to the train and the reaction rail on the guideway needs to be kept within a

prescribed range. There has been a large variety of approaches to designing a controller, which is suitable for similar tasks.

The levitation distance between the magnet and the guideway remains within prescribed boundaries at any time is a fundamental challenge in the control of magnetic levitation (maglev) systems. This problem becomes particularly demanding when further control objectives, such as traveling comfort, control effort, etc., are additionally considered. Due to its ability to take control and state constraints directly into account while addressing additional priorities within the used cost function, MPC is particularly well-suited to balance such different control objectives while adhering to constraints. However, solving such a constrained output regulation problem for nonlinear systems with MPC is still a field of active.[14]

➢ Maglev:

To further exploit the energy advantages of the maglev, we have successfully addressed the critical energy bottleneck issues in the HTS-based linear electromagnetic thruster for the future sustainable ultra-high-speed maglev, and demonstrated a highly energy-efficient prototype in our previous work.

The ultra-high-speed maglev (>600 km/h) has been raising great interest worldwide. Adopting strong magnetic-field high-temperature superconductor (HTS) technology in the maglev is straightforward, to achieve a substantial enhancement in the dynamic performance of the linear electromagnetic thruster. The HTS magnets are the essential part to distinguish a HTS maglev from regular maglevs that use electromagnets or permanent

magnets. With ever-developing HTS technology, the second-generation (2G) HTS REBCO magnets have achieved an unprecedented performance of larger in-magnetic-field current transport capability higher operating temperature and much improved operational stability as compared to LTS counterpart which ensures engineering applications without relying on liquid helium (4.2K).[13]

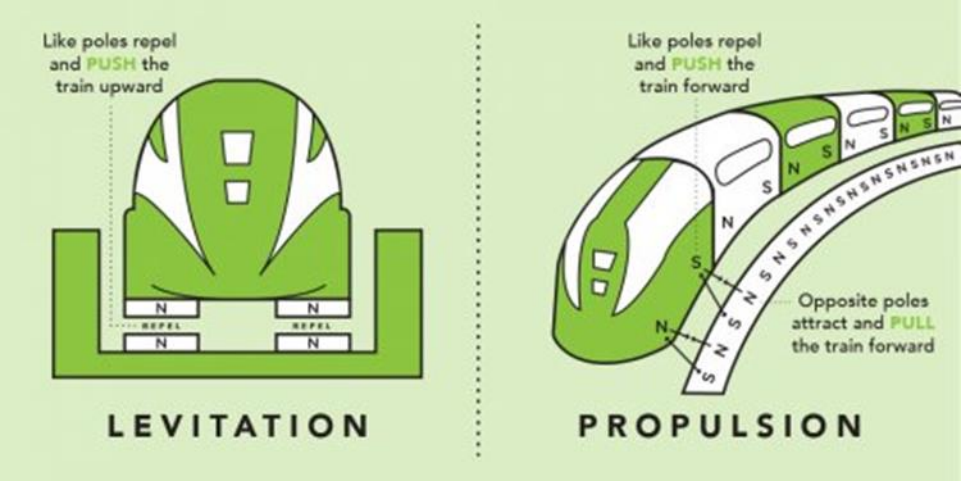


Fig1.03: Maglev levitation

➢ The German Trans-rapid:

This is an electromagnetic levitation (EMS) train, levitation being ensured by electromagnets. The track is equipped with fixed ferromagnetic cores (stator) which attract the electromagnets contained in the lower part of cars. This allows the levitation of the cars when the magnetic force exactly compensates for gravity (Figs). The distance between the electromagnets and the stator is approximately 10mm. The "floor" of cars floats for its leaves about fifteen centimeters above the rail. [13].

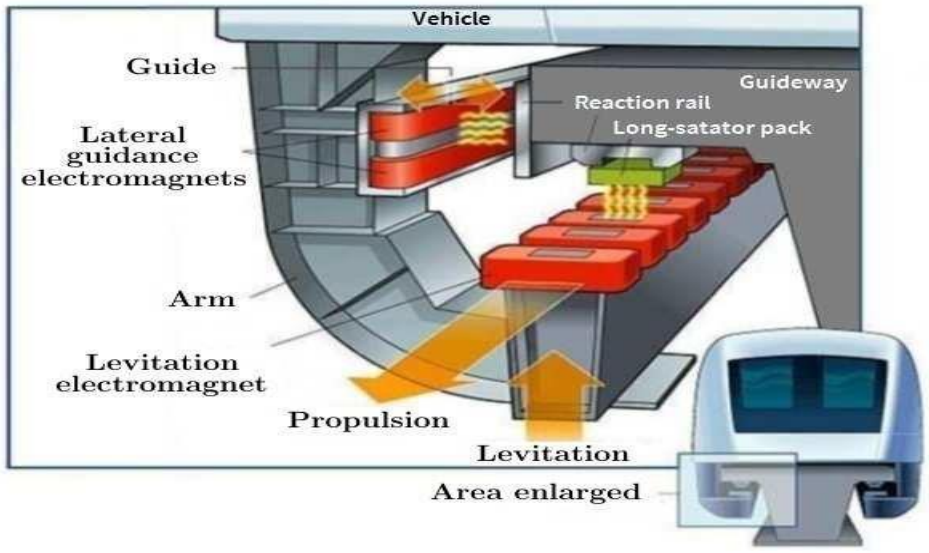


Fig1.04: Allemand trans-rapid.

Ⅰ-6 Conclusion

In this chapter, we discussed the various types of planar magnetic bearings and demonstrated the operation of one type through its application in a magnetic levitation train. Magnetic bearings include active, passive, and hybrid types, each offering unique control and performance characteristics [46], [47]. They enable frictionless, wear-free operation, ideal for high-speed and precision applications [48]. Widely used in aerospace, energy, and vacuum systems, they reduce maintenance and improve reliability [49]. Selection depends on application requirements, balancing control complexity and operating conditions [50].

Chapter II:

Planar Magnetic bearings control techniques.

Ⅱ.1 Introduction:

In this chapter, we focus on two fundamental control strategies widely used in industrial and engineering applications: the Proportional-Integral-Derivative (PID) controller and the Fuzzy Logic Controller (FLC).

We begin by introducing the PID controller, the most commonly used feedback control mechanism due to its simplicity, effectiveness, and ease of implementation. We will examine its mathematical formulation, tuning methods, and performance characteristics in regulating dynamic systems.

Next, we explore the Fuzzy Logic Controller, a more flexible and intelligent control strategy inspired by human reasoning. Unlike traditional controllers that rely on precise mathematical models, fuzzy controllers use linguistic rules and approximate reasoning, making them particularly effective for complex, nonlinear, or poorly modeled systems.

Through this chapter, we aim to provide a comparative understanding of both control methods, laying the foundation for selecting and implementing the appropriate strategy based on system behavior and control objectives.

Ⅱ.2 Control technics

II.2.1 Enslaved system correction

A corrector has the role of adjusting the defects of a system in terms of speed, accuracy and stability. Each defect corresponds to a corrector, but we will see that one type of correction can cause an undesirable behavior, which must also be corrected. In order to improve the performance of an enslaved system, it will be necessary to act on the gap between the setpoint and the output, in order to correct its value before controlling the system.[30]

The transfer function of the system is

$$C(P)=\frac{U(P)}{\varepsilon(P)} \quad (1.1)$$

- The overall structure of such a servitude will therefore be as follows

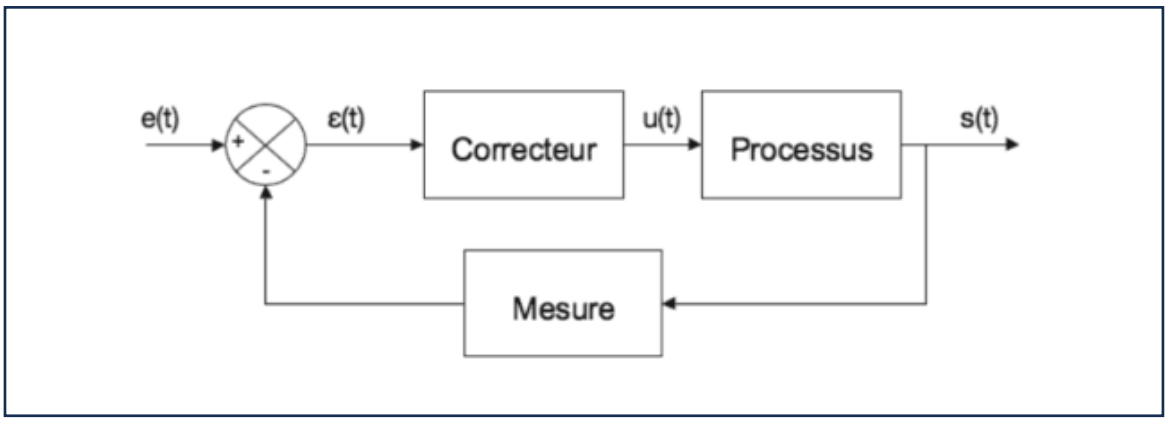


Fig2.01:overall structure of system [18]

II.2.1.1 Proportional correction P

The proportional correction generally serves to quickly arrive at the setpoint value. If we use a proportional type corrector consisting of a “K” gain amplifier, we Gets a command law that is proportional to the error: [18]

U(t)=Kp*e(t) (1.2)

The proportional corrector P acts directly on the error at the current time to generate the action required to correct the dynamic behavior of the quantity to be controlled. The response of such a corrector is instantaneous. The transfer function of proportional corrector is:

C(P)=$\frac{U(P)}{\varepsilon(P)}$ = Kp. (1.3)

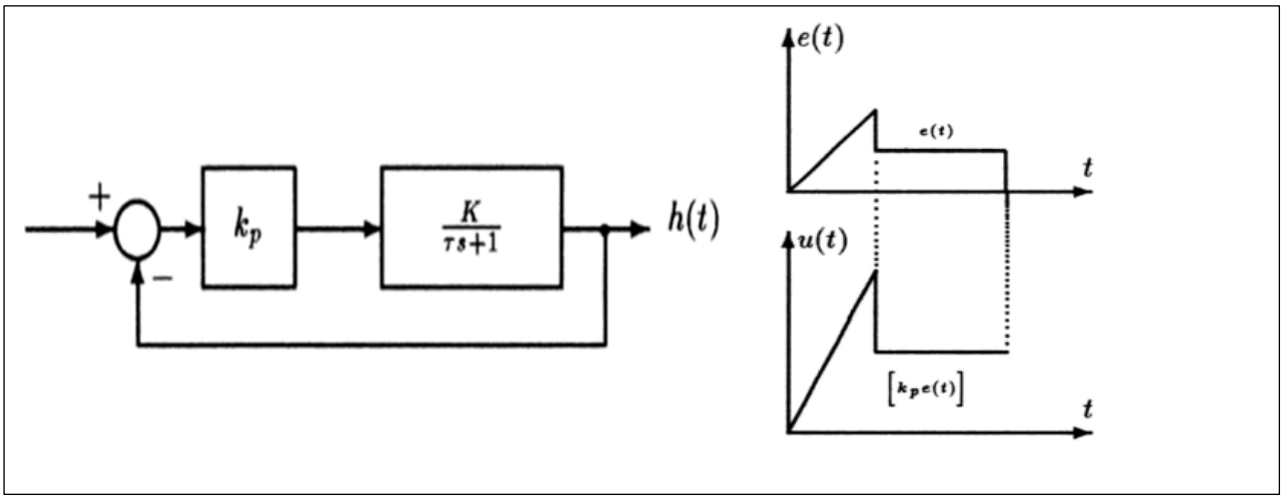


Fig2.02:overall structure and result of a P corrector[18]

II.2.1.2 Integral correction I

In order to overcome the above-mentioned inconvenience, the integral type corrector is of great importance because it increases the type of system by one unit and therefore improves the permanent regime. The major disadvantage of this type of corrector is the addition of a pole at the origin of the plane, which causes a stability degradation effect.[18]

$$u(t) = kI \int_0^t e(\tau)\, d\tau \quad (1.4)$$

The transfer function of the system in this case is:

$$C(P)=\frac{U(P)}{\varepsilon(P)}=\frac{k_I}{P} \quad (1.4)$$

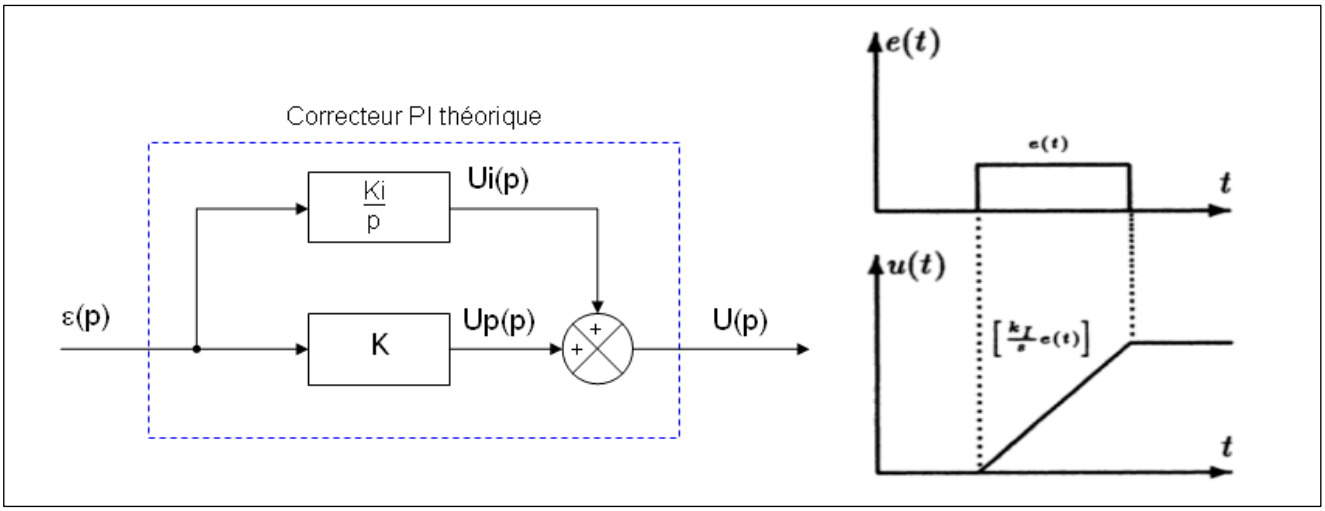


Fig2.03:overall structure and result of a I corrector [37]

II.2.1.3 Derivative correction D

The integral corrector produces a control signal even if the signal has reached the steady state, which is the major disadvantage of this corrector. One possibility to avoid this is to design a corrector that reacts to the error signal derivative. Thus, the corrector produces a single action when the error signal varies. When the rate of variation of the error signal e(t) at current time is large, the amplitude of the error signal takes a large value in the future. The use of the derivative corrector produces a forward correction that reduces the error. The main advantage of the derivative corrector is that it predicts the future evolution of the error and acts accordingly to counteract this evolution. This type of corrector has no permanent effect. [18]

$$U(t)=K_D \frac{d}{dt}e(t) \quad (1.5)$$

The transfer function is :

$$C(P)=\frac{U(P)}{\varepsilon(P)}= K_D P \quad (1.6)$$

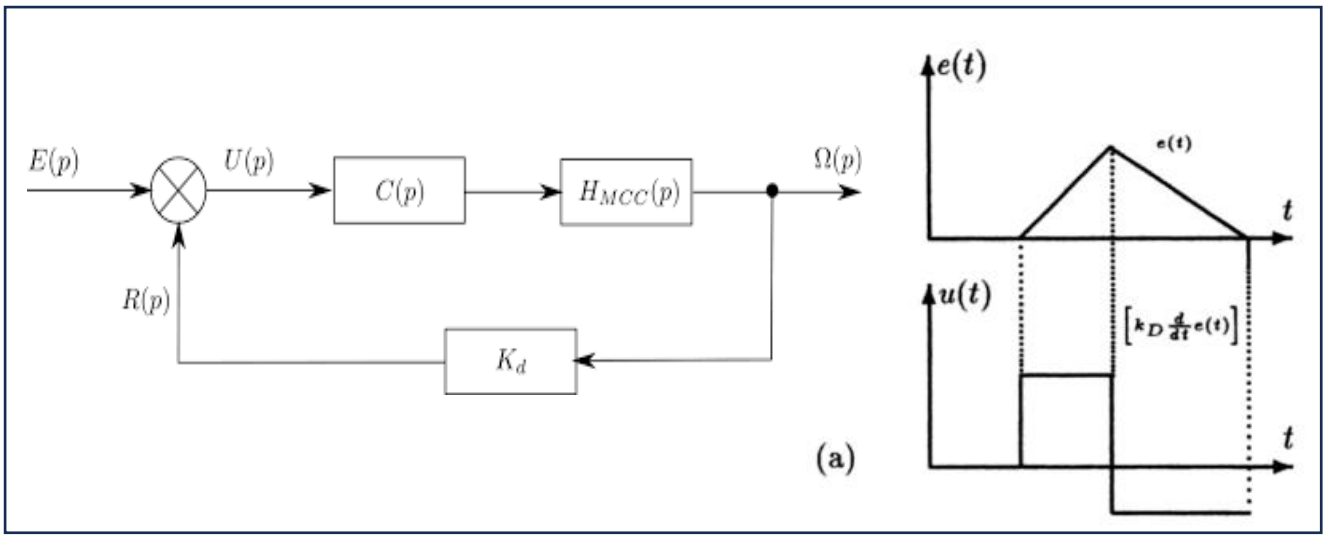


Fig2.04:overall structure and result of a D corrector [38]

II.2.1.4 Integral proportional correction PI

The PI corrector frequently combined with two correctors. This combination is called an integral-proportional corrector. The reason for this combination is that the integral corrector improves the permanent regime while worsening the transitional regime. Proportional representation offers the possibility of amending both the transitional regime and the permanent regime. The full proportional corrector then combines both advantages and thus improves both the permanent regime and the transitional regime.[32]

$$u(t)=K_P*e(t)+ K_I \int_0^t e(\tau)d\tau \quad (1.7)$$

the transfer function is :

$$C(P)=\frac{U(P)}{\varepsilon(P)}=\frac{k_I}{P}+Kp+\frac{P+Z}{P}\ ,\ Z=\frac{K_I}{K_P} \qquad (1.8)$$

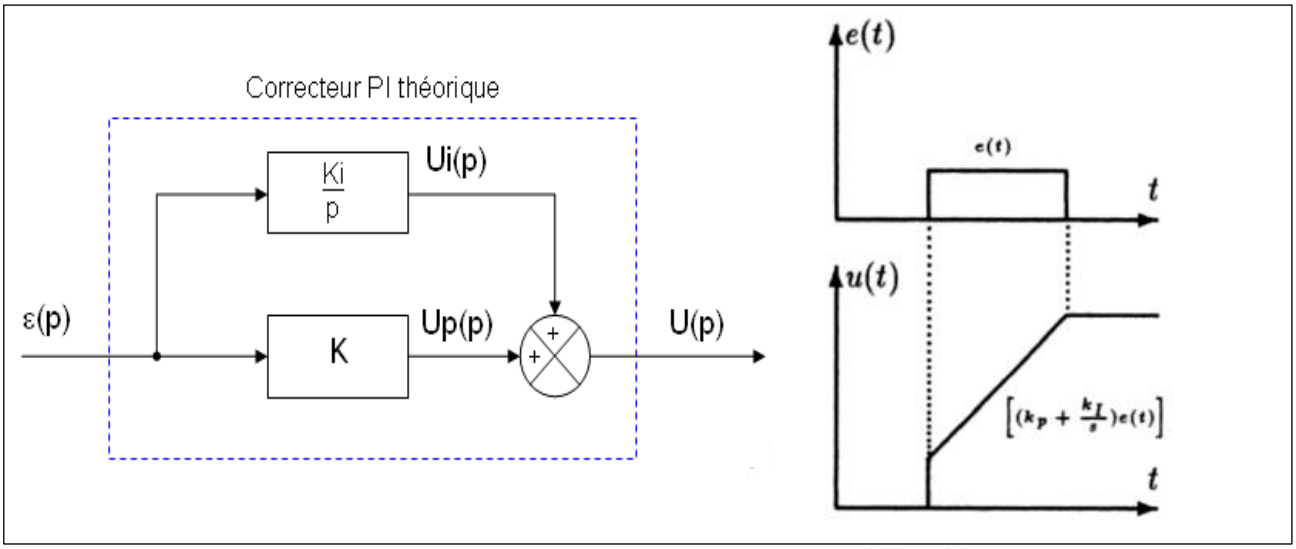


Fig2.05:overall structure and result of a PI corrector [37]

II.2.1.5 Derivative proportional correction PD

The major disadvantage of the derivative corrector is its insensitivity to slow error variations. For this reason, this type of corrector is never used alone. A solution to minimize this disadvantage is to use the proportional-derivative corrector. The equation for this type of corrector in the time domain is given by the following relation:[27]

$$u(t)=K_P\ e(t)+K_D\frac{de}{dt}(t) \qquad (1.9)$$

and his transfer function :

$$C(P)=\frac{U(P)}{\varepsilon(P)}=P*k_D+Kp=K_D(P+Z)\ ,\ Z=\frac{Kp}{k_D} \qquad (1.10)$$

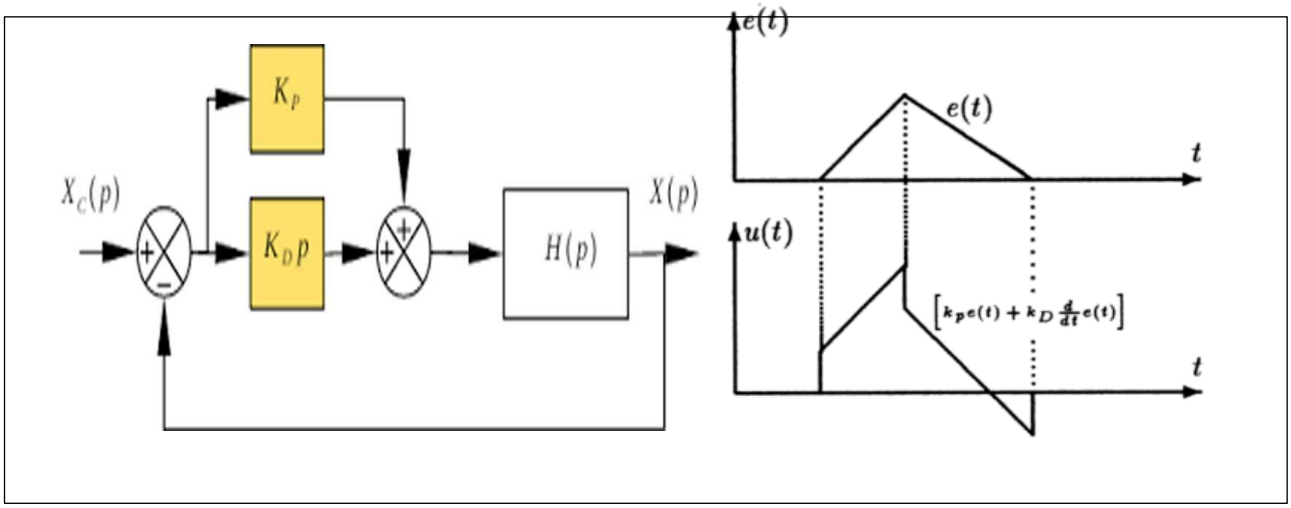


Fig2.06:overall structure and result of a PD corrector [18]

II.2.1.6 The PID corrector

The proportional-integral-derivative corrector is a widely used corrector industry because of its simplicity. It consists of three actions: in

- proportional action (P);
- the integral action (I);
- the derivative action (D).

This corrector placed in the direct chain of a servo system acts on the error of the system to produce the appropriate signal to the actuator in order to reduce this gap between the set point and the output value. By calling this signal u(t), we have:[18]

$$u(t)=K_P\, e(t)+K_I \int_0^t e(\tau)d\tau+K_D \frac{d}{dt}e(t) \qquad (1.11)$$

And the transfer function :

$$C(P)=\frac{U(P)}{\varepsilon(P)} = Kp + \frac{KI}{P} + P * Kd \quad (1.12)$$

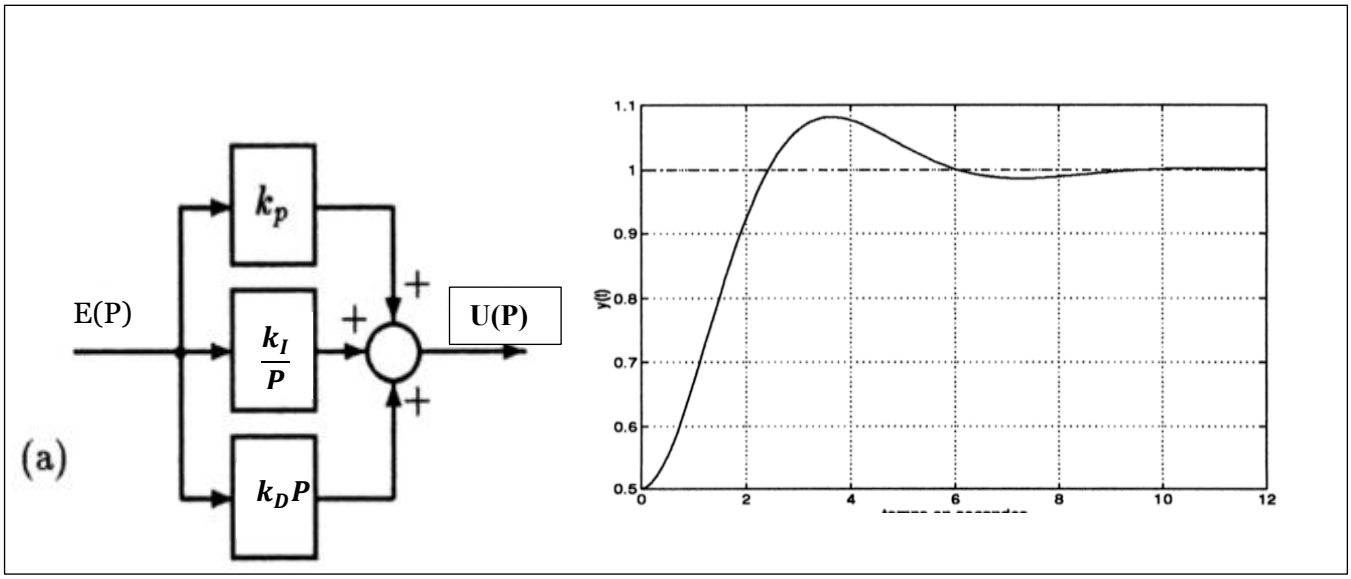


Fig2.07:overall structure and result of a PID corrector [18]

II.2.1.7 Practical determination of the parameters of a corrector

In a practical way, to set the parameters of the controller that allow to obtain a Satisfactory response of the controlled system, the following steps are followed:

1-First the open loop response is simulated and the effects to be corrected are determined.

2. Proportional control is introduced to improve system climb time enslaved.

3. the derivative command is introduced to improve the overshoot.

4. Full control is introduced to eliminate static error.

5. Each of the parameters of the corrector is adjusted, and until a response is obtained satisfactory.[28]

II.2.2 Stability study

II.2.2.1 Definition of the location of the poles (root locus)

The pole placement technique (root locus)is a method for synthesizing correctors that allows you to study on a diagram the influence of a setting parameter on the position of the poles of the loop system closed. It is known that the properties of linear systems are directly related to Location of the poles and zeros of the closed loop system transfer function.

The influence of gain k on the root location of the transfer function will be discussed closed loop. The root location of an open-loop transfer function is the graph representing the Rental of all poles in the closed loop system with a single return and gain proportional.[18]

II.2.3 Correction by Fuzzy logic (Fuzzy control)

The fuzzy control technique was first initiated by the pioneering research of Mamdani (Mamdani, 1974, 1977; Mamdani and Assilian, 1975)[36] for systems structurally difficult to model, which was motivated by Zadeh's paper on system analysis with fuzzy sets theory (Zadeh, 1965, 1968, 1973, 1975). Since then, fuzzy control theory has become one of the most extensively studied areas in both academia and industry. Many theoretical developments and practical applications have been reported. It is an appealing alternative to conventional control methods since it provides a systematic and efficient framework to deal with uncertainties and nonlinearities in complex systems, when an accurate system analytical model is not available, not possible to obtain, or too complicated to use for control purposes. In this chapter, different fuzzy control schemes are explained in each section with individual example to give readers an easy understanding of the fuzzy controllers; working principle.

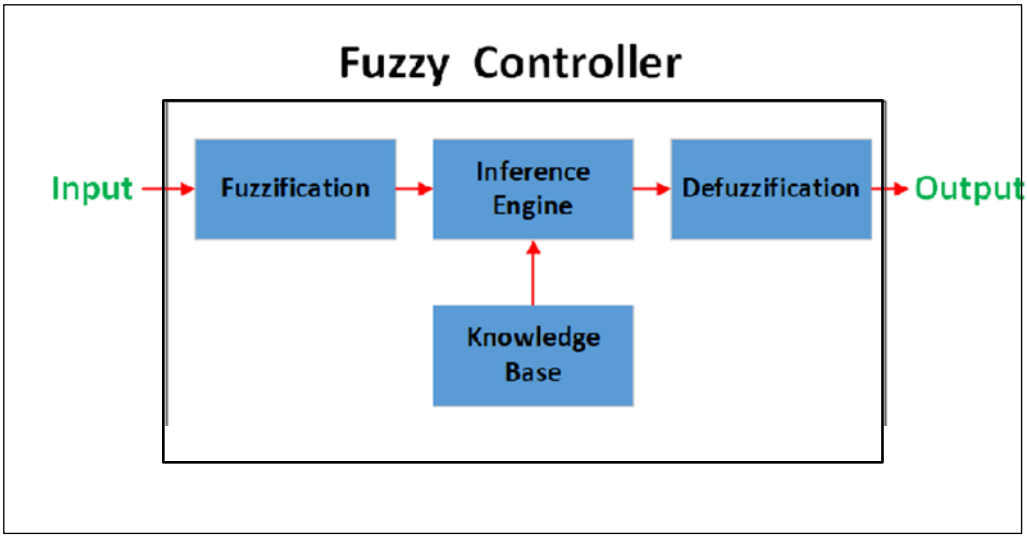


Fig2.08: Control by fuzzy controller [39]

II.2.3.1 Applications of Fuzzy logic in wireless communications

Here are some examples of techniques and applications of fuzzy logic in wireless

Communication:

1. Channel equalization
2. Handover management
3. Quality of service management (QoS)
4. Modulation scheme selection
5. Power control
6. Channel prediction
7. Resource allocation[28]

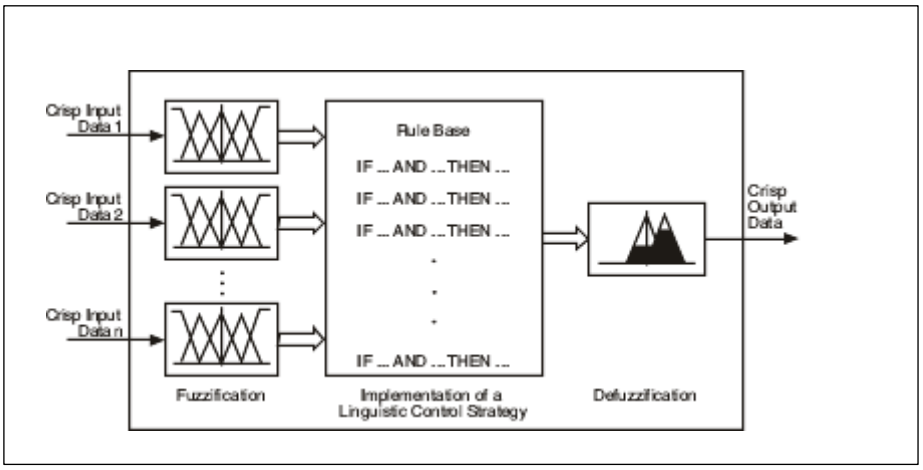


Fig2.09: Structure of a Fuzzy Logic Controller[35]

II.2.3.2 Advantages and disadvantages of using Fuzzy logic in these application

a. Advantages :

1. **Robustness:** Fuzzy logic is robust to noise, uncertainty, and imprecision in the wireless channel, which can help improve the reliability of the wireless link.[23]
2. **Adaptability:** Fuzzy logic can adapt to changing network conditions, user requirement and application demands, which can help to optimize the wireless link.
3. **Flexibility:** Fuzzy logic provides a flexible approach to wireless communication, which can handle a wide range of channel conditions, network topologies, and user scenarios.
4. **Intuitiveness:** Fuzzy logic is easy to understand and interpret, which can help designes and users of wireless communication systems to make informed decisions.
5. **Efficiency:** Fuzzy logic is computationally efficient and can be implemented in real time systems, which can help reduce the processing delay and energy consumption of wireless devices. Mathematical Modelling Techniques and Applications of Wireless Communication

b. Disadvantages

1. **Complexity:** Fuzzy logic can be complex and difficult to design, which can require expertise in both fuzzy logic and wireless communication.
2. **Overfitting:** Fuzzy logic can overfit the data and the model, which can lead to poor generalization and performance degradation in real-world scenarios.
3. **Tuning:** Fuzzy logic requires tuning of the parameters and rules, which can be time-consuming and challenging to optimize.
4. **Interpretability:** Fuzzy logic can be difficult to interpret and explain. Which can limit its use in safety-critical and mission-critical applications.[23]

The advantages of using fuzzy logic in wireless communication outweigh the disadvantages, and the use of fuzzy logic can help address many of the challenges and issues in wireless networks. However, the design and implementation of fuzzy logic-based algorithms require careful consideration of the trade-offs between the benefits and the costs of using fuzzy logic[18].

II.4 Conclusion

In this chapter, we have presented the various control techniques on which our system study is based. In summary, theory supports using PID and PD controllers for simpler, linear systems, while fuzzy logic controllers offer improved robustness and adaptability in nonlinear, uncertain environments

ChapterIII:

Analytical Modeling of the Planar Bearing

Ⅲ-1 Introduction :

This chapter presents the modeling and control design aspects necessary for implementing efficient control strategies. We begin by developing a **mathematical model** of the system, which is a critical step for understanding system dynamics and predicting its behavior under various inputs and control actions.

Once the model is established, we apply the technique of **pole placement using a PID controller**. This approach allows us to tune the controller parameters to position the system poles in locations that ensure desired performance characteristics such as stability, responsiveness, and damping.

In the latter part of the chapter, we turn our focus to the **fuzzy control system**, specifically the construction of the **fuzzy rule table**. This table defines the controller's behavior based on a set of linguistic rules that relate input variables (such as error and its derivative) to output control actions. The rule base is essential for capturing expert knowledge and handling nonlinearities in the system.

By integrating both analytical and heuristic design methods, this chapter bridges the gap between classical and intelligent control strategies.

Ⅲ-2 Analytical Modeling:

Ⅲ-2-1 Magnetic force model:

$$F(x,i) = k * (\frac{i}{x})^2 \qquad (2.01)$$

- $x(\mathrm{t})$: position (output).
- $i(\mathrm{t})$: input (current or control variable).

 k: constant from system physics.

✓ Linearize $F(x,i)$ using first-order Taylor expansion.

Define:

- $\Delta x = x - x_0$ (2.02)
- $\Delta i = i - i_0$ (2.03)

✓ The partial derivative:

$$\frac{\partial F}{\partial x} = \frac{-2ki^2}{x^3} \Longrightarrow kx = \left|\frac{\partial F}{\partial x}\right| = \frac{2ki_0^2}{x_0^3} \quad (2.04)$$

$$\frac{\partial F}{\partial i} = \frac{-2ki}{x^2} \Longrightarrow ki = \left|\frac{\partial F}{\partial i}\right| = \frac{2ki_0}{x_0^2} \quad (2.05)$$

$$\begin{cases} kx = \frac{2ki_0^2}{x_0^3} \\ ki = \frac{2ki_0}{x_0^2} \end{cases} \quad (2.06)$$

Ⅲ-2-2 Newton's low (Dynamic Equation):

$$m\ddot{x} = \sum \vec{F} \quad (2.08)$$

$$m\ddot{x} = k_i\, i - k_x\, x + mg - F_0 \quad (2.09)$$

$$m\ddot{x} = k_i\, i - k_x\, x \quad (2.10)$$

III-2-3 Transfer function:

Applying Laplace transform:

$$ms^2X(s) = -k_x\, X(s) + k_i\, I(s) \quad (2.11)$$

$$X(s) = \frac{k_i}{ms^2+k_x} I(s) \quad (2.12)$$

$$H(s) = \frac{X(s)}{I(s)} = \frac{k_i}{ms^2+k_x} \quad (2.13)$$

Ⅲ-3 Control by Pole placement method for systems:

Ⅲ-3-1 PID controller:

The poles of a third-order system are:

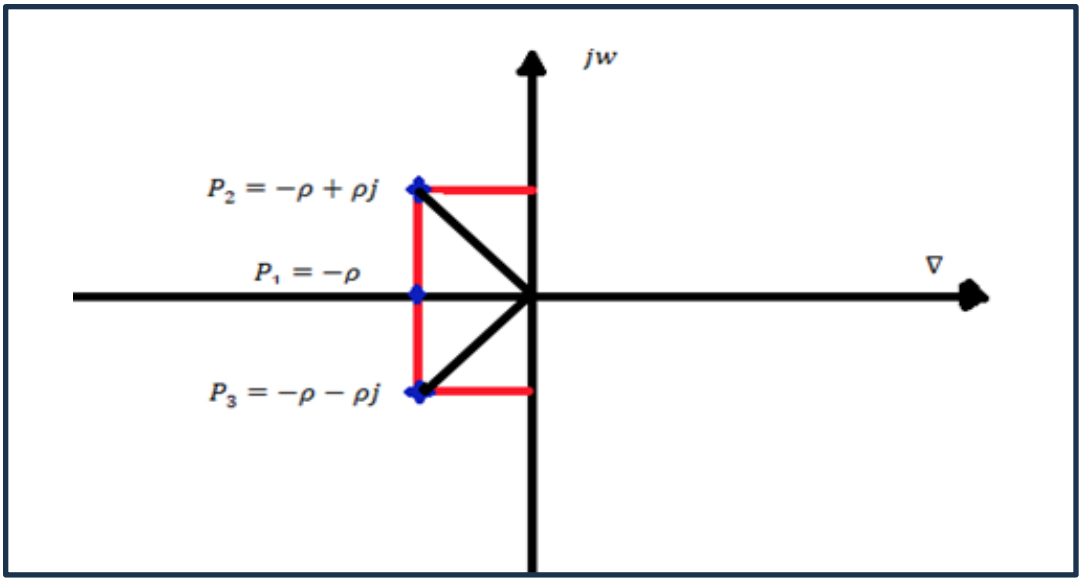


Fig 3.01: Pole Zone for Stable Response in a Third-Order System

$$P_1 = -\rho \quad (2.14)$$

$$P_2 = -\rho + \rho j \quad (2.15)$$

$$P_3 = -\rho - \rho j \quad (2.16)$$

$$(s - P_1)(s - P_2)(s - P_3) = s^3 + 3\rho s^2 + 4\rho^2 s + 2\rho^3 \quad (2.17)$$

✓ The Transfer function of PID controller is :

$$c(s) = \frac{k_d\, s^2 + k_p\, s + k_i}{s} \tag{2.18}$$

The characteristic equation of the system (2.13) with the transfer function (2.18) of the PID controller in closed loop is:

$$G(s) = \frac{(k_d s^2 + k_p s + k_i^{(pid)}) k_i}{s(ms^2 + k_x) + k_i (k_d s^2 + k_p s + k_i^{(pid)})} \tag{2.19}$$

$$\mathrm{G(S)} = \mathrm{s}^3 + \frac{\mathrm{k_i\, k_d}}{\mathrm{m}}\, \mathrm{s}^2 + \frac{(\mathrm{k_i\, k_p + k_x})}{\mathrm{m}}\, \mathrm{s} + \frac{\mathrm{k_i\, k_i^{(pid)}}}{\mathrm{m}} \tag{2.20}$$

- By matching (2.16) with (2.19) we find :

$$k_p = \frac{4m\rho^2 - k_x}{k_i} \tag{2.21}$$

$$k_i^{(pid)} = \frac{2m\rho^3}{k_i} \tag{2.22}$$

$$k_d = \frac{3\rho m}{k_i} \tag{2.23}$$

III-3-2 PD controller:

The poles of a second-order system are:

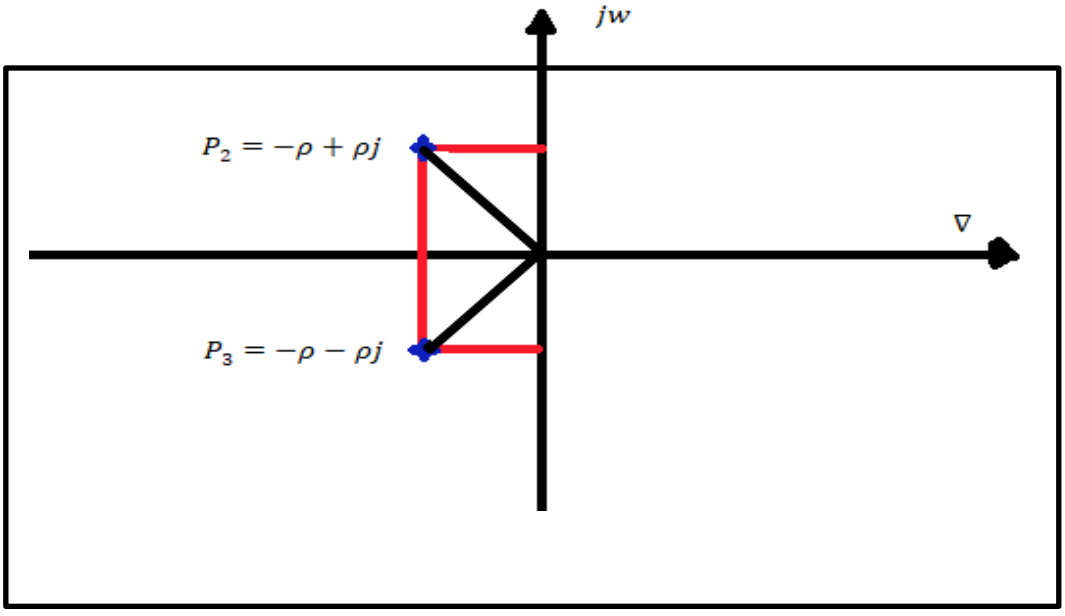


Fig3.02: Pole Zone for Stable Response in a second-Order System.

$$P_1 = (-\rho + j\rho) \quad (2.24)$$

$$P_2 = (-\rho - j\rho) \quad (2.25)$$

$$(s - P_1)(s - P_2) = s^2 + 2\rho s + 2\rho^2 \quad (2.26)$$

✓ The Transfer function of PD controller is :

$$C(s) = k_p + k_d s \quad (2.27)$$

The characteristic equation of the system (2.12) with the transfer function (2.26) of the Pd controller in closed loop is:

$$G(s) = \frac{k_d s + k_p + k_i}{ms^2 + k_d k_i s + k_x + k_p k_i} \quad (2.28)$$

$$G(s) = s^2 + \frac{k_d k_i}{m} s + \frac{k_x + k_p k_i}{m} \quad (2.29)$$

- By matching (2.24) with (2.29) we find :

$$k_p = \frac{2\rho^2 m - k_x}{k_i} \quad (2.30)$$

$$k_d = \frac{2\rho m}{k_i} \quad (2.31)$$

III-4 Fuzzy control method :

Fuzzy control is one of the advanced control methods, aimed at achieving better performance compared to classical control systems (such as PID, PD, PI, etc.). The fuzzy controller operates in discrete mode, and its inputs are the estimated value and the derivative of that value (in our case, the estimated value represents the position error).[33]

It is also possible to add input and output gains to the fuzzy controller. These gains are selected based on the specific system in order to enhance its stability.

The fuzzy controller block is implemented in MATLAB Simulink using a set of predefined rules. Through these rules, the controller adjusts the estimated value of the controlled variable

until it matches the reference value (target position), effectively minimizing the error between them. In our case, the selected fuzzy rules are:

rules. Through these rules, the controller adjusts the estimated value of the controlled variable

until it matches the reference value (target position), effectively minimizing the error between them. In our case, the selected fuzzy rules are:

These regulator levels, or fuzzy rules, continuously adjust the estimated value at each time step and system state until the estimated value matches the reference value. If we consider the first row and the first column of the fuzzy rule table, we get the following condition:

- If the input is negative and the derivative of the input is also negative, then the regulator output should vary in the negative direction.

This means that the controller interprets this situation as requiring a decrease in the output value in order to reduce the error.

U DU	Nb	Nm	Ns	Z	Ps	Pm	Pb
Nb	Nb	Nb	Nb	Nb	Nm	Ns	Z
Nm	Nb	Nb	Nb	Nm	Ns	Z	Ps
Ns	Nb	Nb	Nm	Ns	Z	Ps	Pm
Z	Nb	Nm	Ns	Z	Ps	Pm	Pb
Ps	Nm	Ns	Z	Ps	Pm	Pb	Pb
Pm	Ns	Z	Ps	Pm	Pb	Pb	Pb
Pb	Z	Ps	Pm	Pb	Pb	Pb	Pb

Table01:conditions of fuzzy control

U: The regulator input

ΔU: The derivative of the input

Nb: negative big

Nm: negative medium

Ns: negative small

Z: The zero level

Ps: positive small

Pm: positive medium

Pb: positive big

III-5 Conclusion :

in this chapter, we've presented the analytic modulization of different magnetic bearing control systems. Analytical modeling of planar bearings is essential for predicting dynamic behavior and ensuring system stability . It supports effective controller design and optimization, enabling reliable performance in precision applications .

Chapter IV:
Control of a Planar Magnetic Bearing

IV-1 Introduction :

In this chapter we will put the results obtained by the calculations carried out, we will first carry out a simulation in Matlab Simulink by three different regulators (PID, PD and fuzzy). To confirm the stability of our system we will study the stability by different diagrams, the results obtained by the calculations will be approved that our system is stable.

IV-2 Control by a PID controller :

The regulator coefficients were calculated by the pole placement method. They are given by the following values:

$k_p = 678.0735$ $k_i^{(pid)}$=2.4519× 10^3 $k_d = 126.1246$

The following control simulation was performed using the Matlab Simulink :

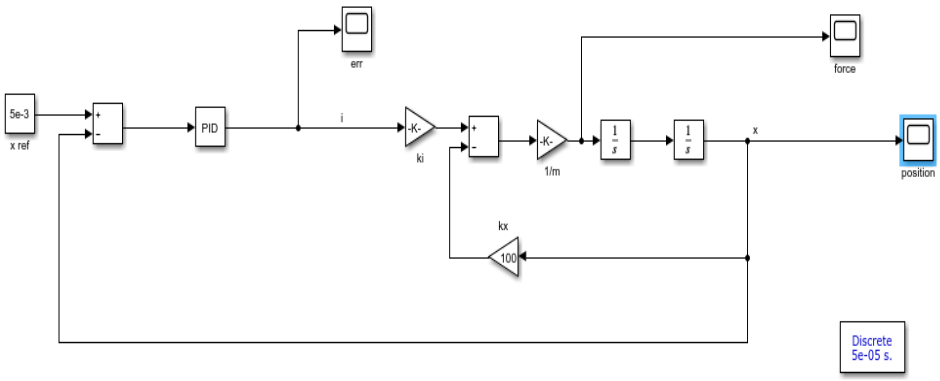


Fig4.01: Matlab simulink of control by a PID controller .

The position variation curve as a function of time shows that the system is stable after 2.5s. This is the time required for the flat moving part to return to the stationary state.

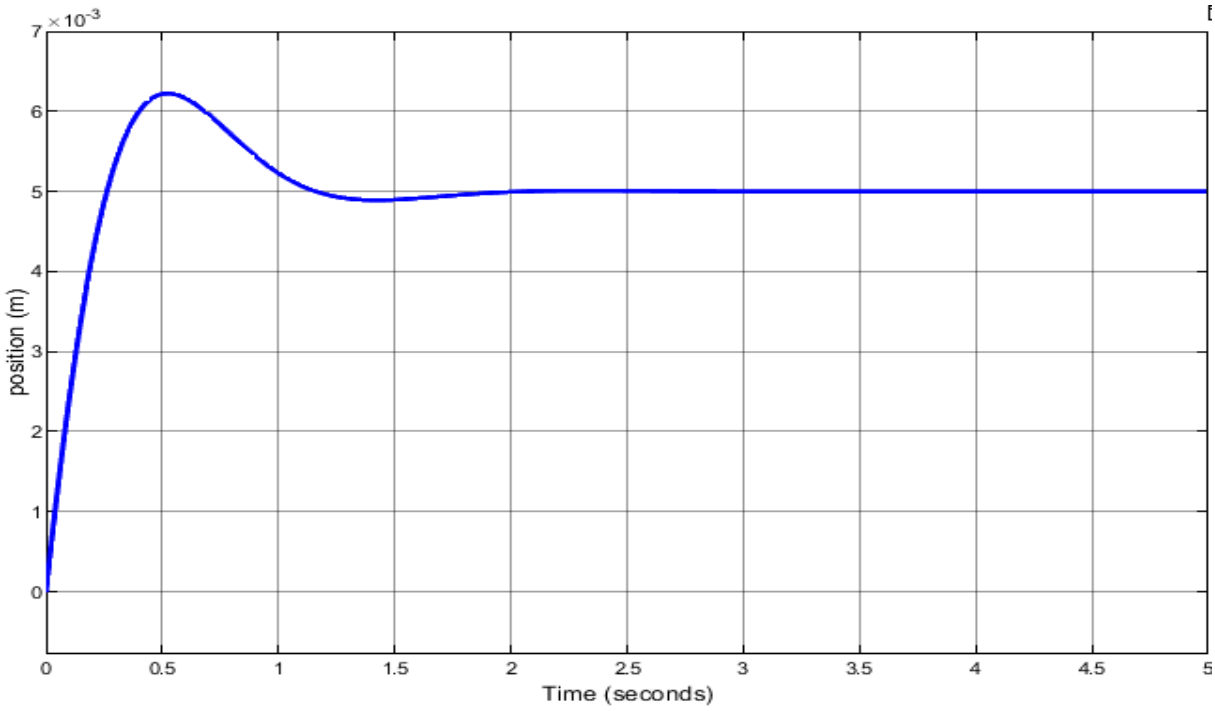


Fig4.02: System response for a desired position of 5×10^{-3}m by PID controller.

On its part, the electromagnetic force takes a stability value after the same time as those of the position. The force tends towards zero after this time, this is very logical because the latter is eliminated by the force of gravity during stability.

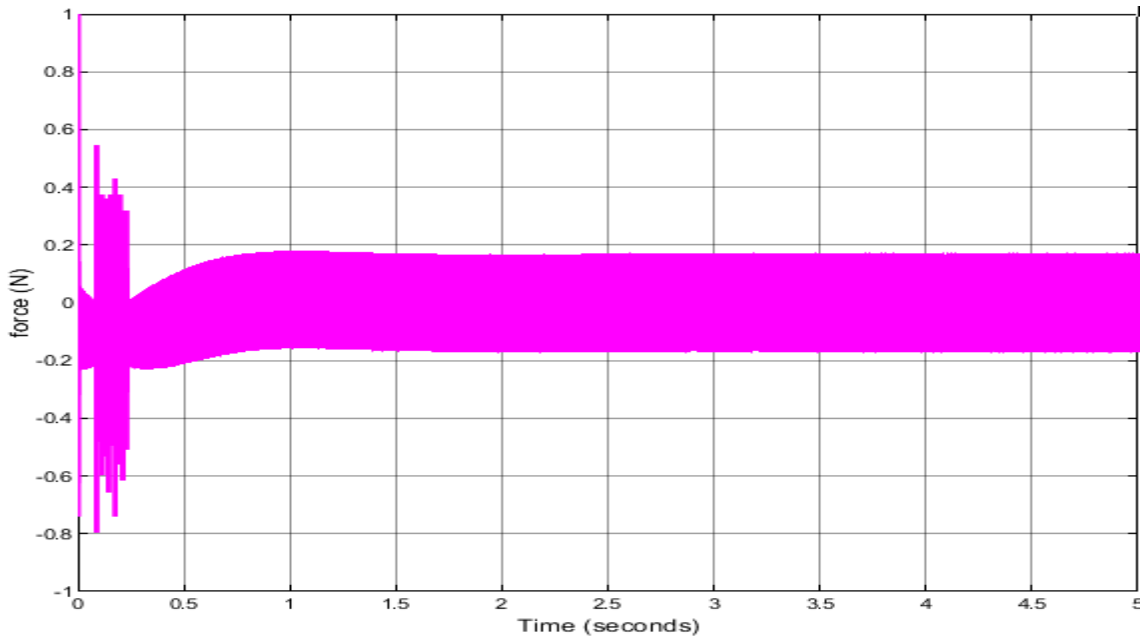


Fig4.03: The electromagnetic force of the system.

During the stability of the electromagnetic system we can clearly notice that the position error which is the difference between the reference position (setpoint) and the estimated value is zero, which confirms that the two values are equal.

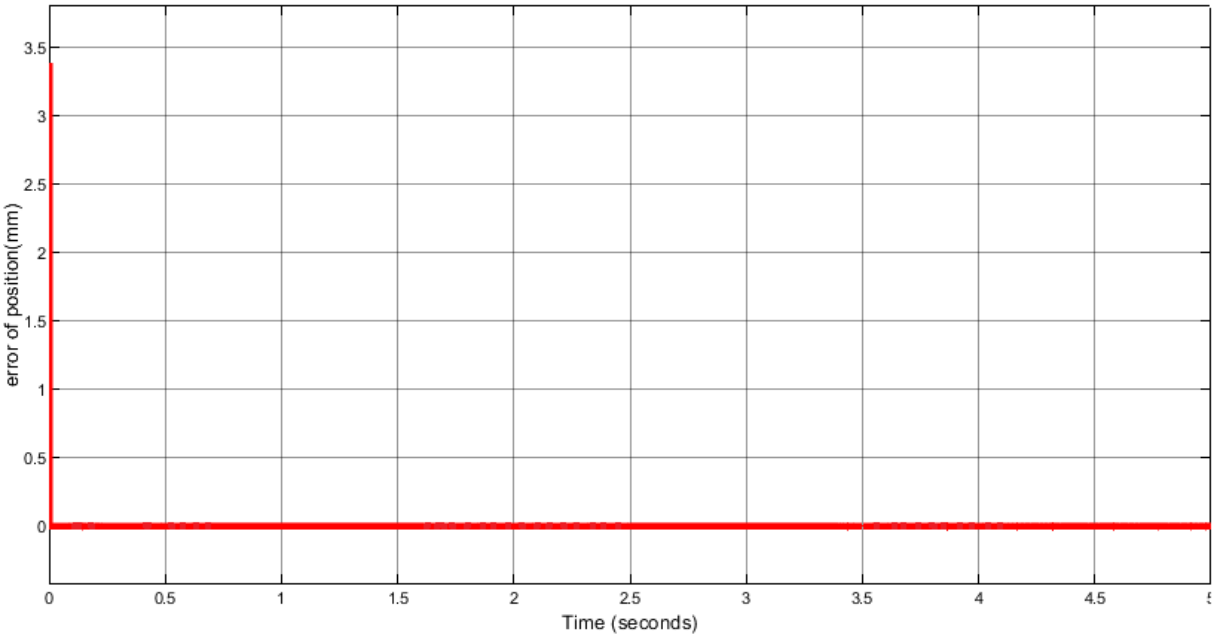


Fig4.04: The error between the reference position and the estimated.

IV-3 Control by a PD controller:

The regulator coefficients were calculated by the pole placement method. They are given by the following values:

$k_p = 678.0735$ $k_d = 126.1246$

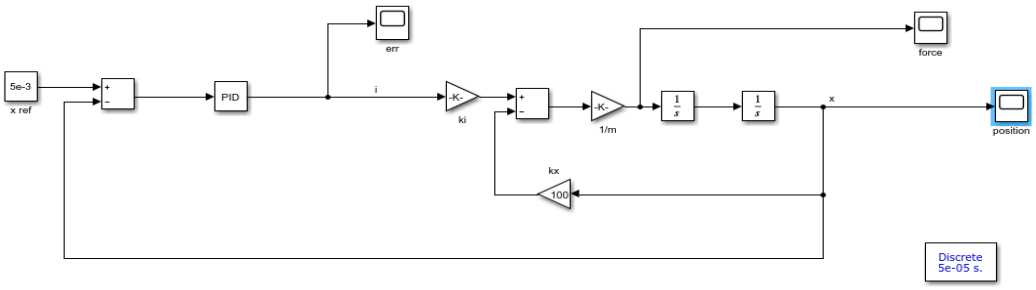


Fig4.05: Matlab simulink of control by a PD controller.

The position variation curve as a function of time shows that the system is stable after 1.4s. This is the time required for the flat moving part to return to the stationary state.

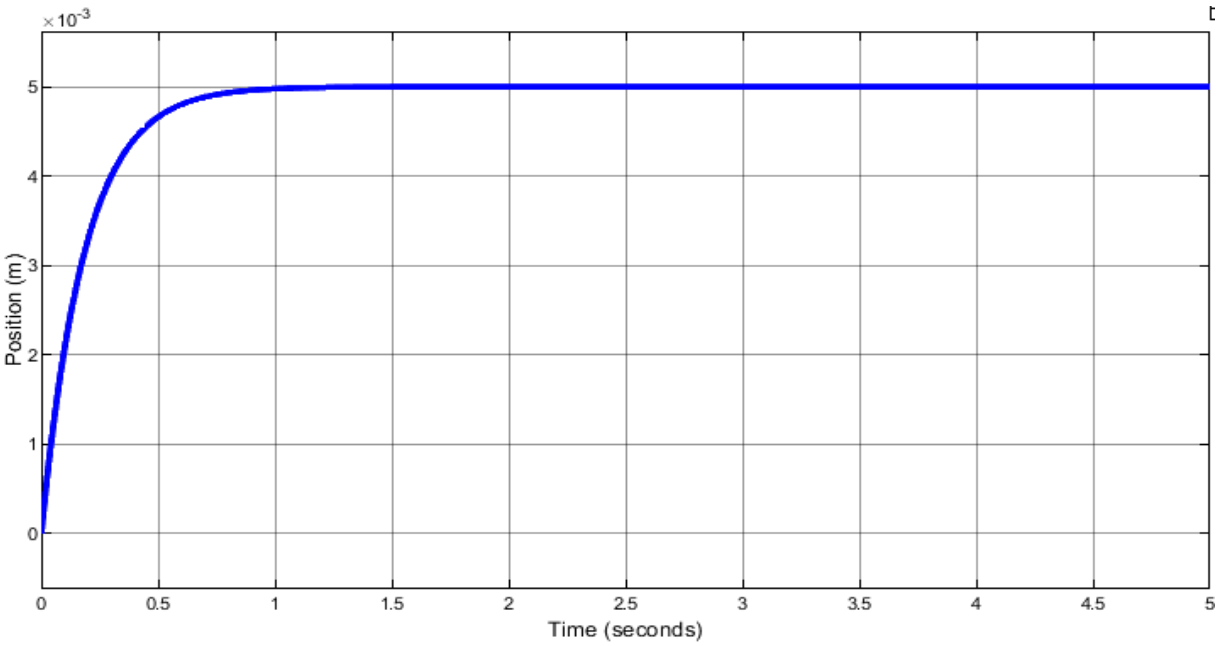


Fig4.06: System response for a desired position of 5×10^{-3}m by PD controller .

On its part, the electromagnetic force takes a stability value after the same time as those of the position. The force tends towards zero after this time, this is very logical because the latter is eliminated by the force of gravity during stability.

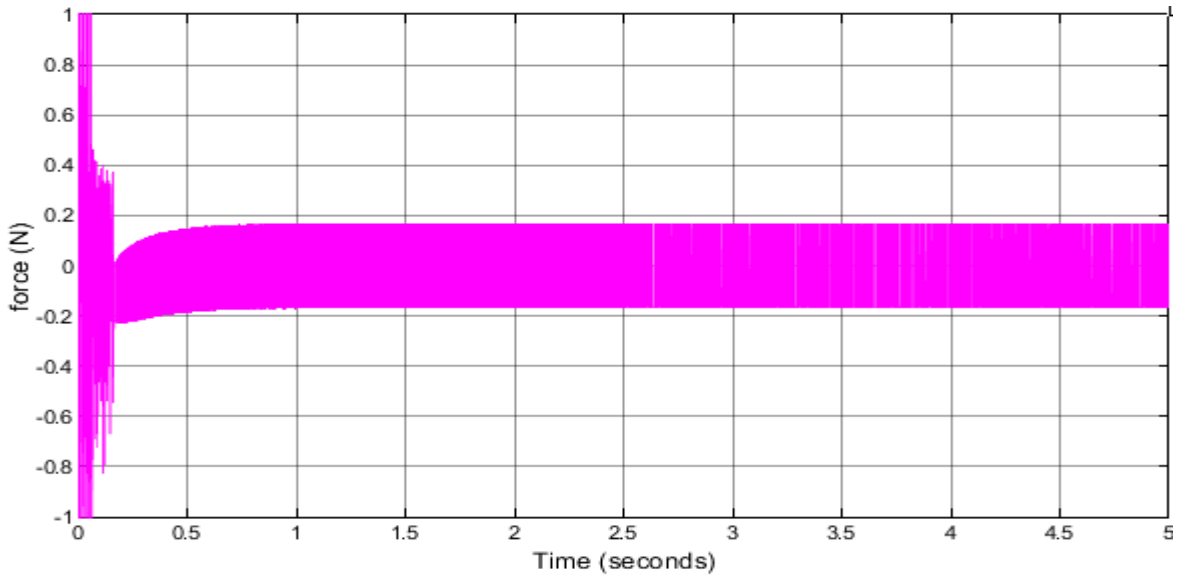


Fig4.07: The electromagnetic force of the system of control by a PD controller.

During the stability of the electromagnetic system we can clearly notice that the position error which is the difference between the reference position (setpoint) and the estimated value is zero, which confirms that the two values are equal.

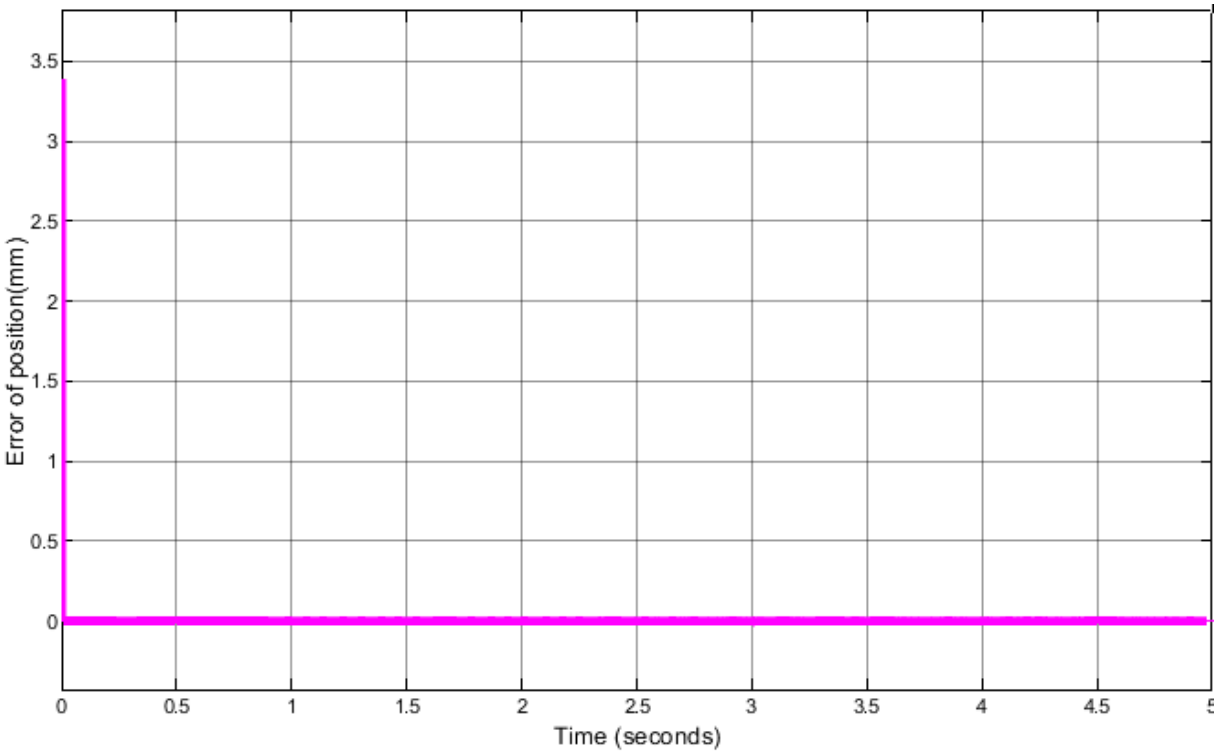


Fig4.08: The error between the reference position and the estimated by PD controller.

- **Remark:**

we notice that the force and error of the PID controller are the same as those of the PD controller.

IV-4 Control by a Fuzzy controller:

IV-4-1 Diagram under MATLAB (Simulink):

Block diagram: The graphic depicts our simulation's block diagram, which includes the setpoint, closed-loop control, mathematical model of the system, and visualization tools.

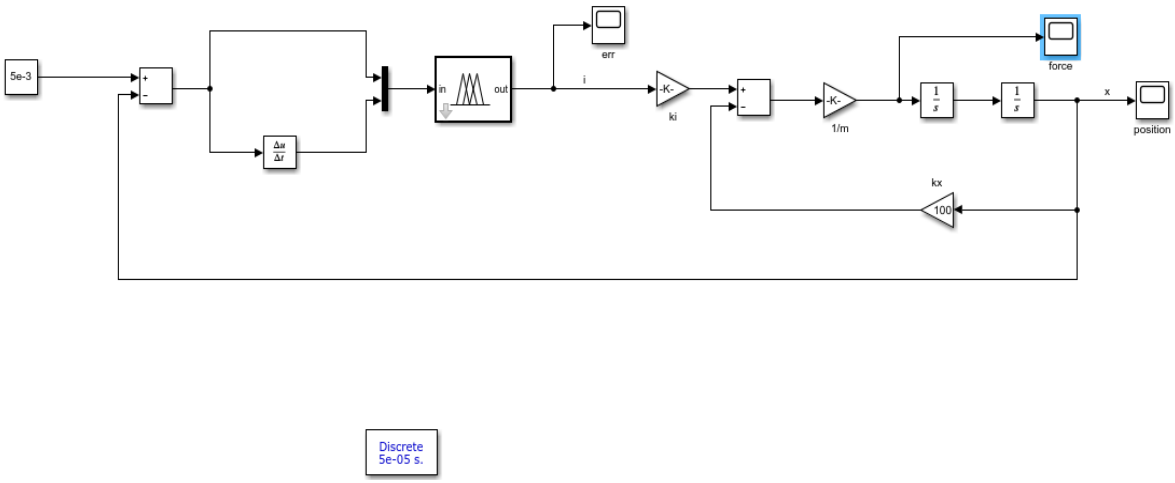


Fig4.09: Matlab simulink of control by a Fuzzy controller.

IV-4-2 Regulator diagram:

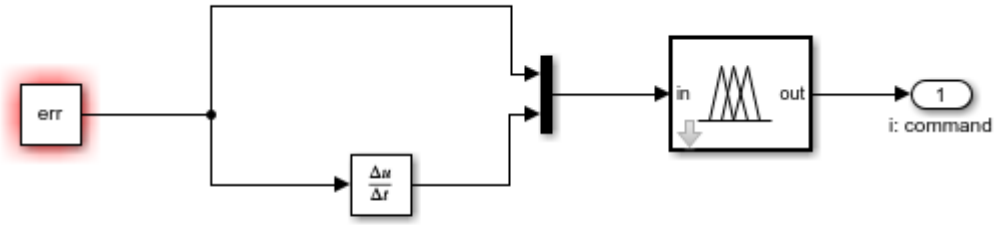


Fig4.10: Fuzzy regulator.

IV-4-2 The operation of a fuzzy controller:

- **Linguistic variables:**

The following are the linguistic variables we selected for the system under study in our project:

The first variable is the error, between the ball's actual location and the desired position as determined by the setpoint level. The second variable is the error's derivative. With the two linguistic variables selected, we can use the derivative of the error to gain an understanding of the response time, stability, and the difference between the desired and actual positions of the ball.

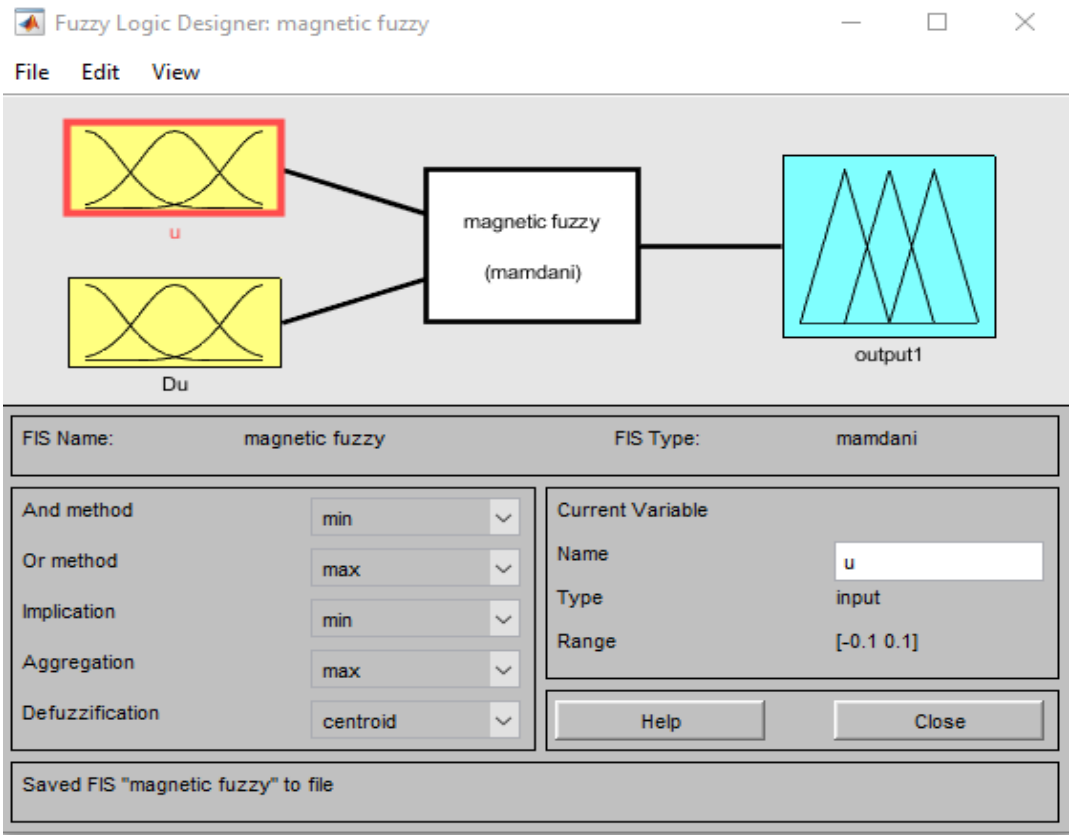


Fig4.11: Fuzzy logic designer.

- **Membership functions:**

The membership functions are triangular functions. While respecting the error domain and the error derivative, all controller inputs are included in this domain.

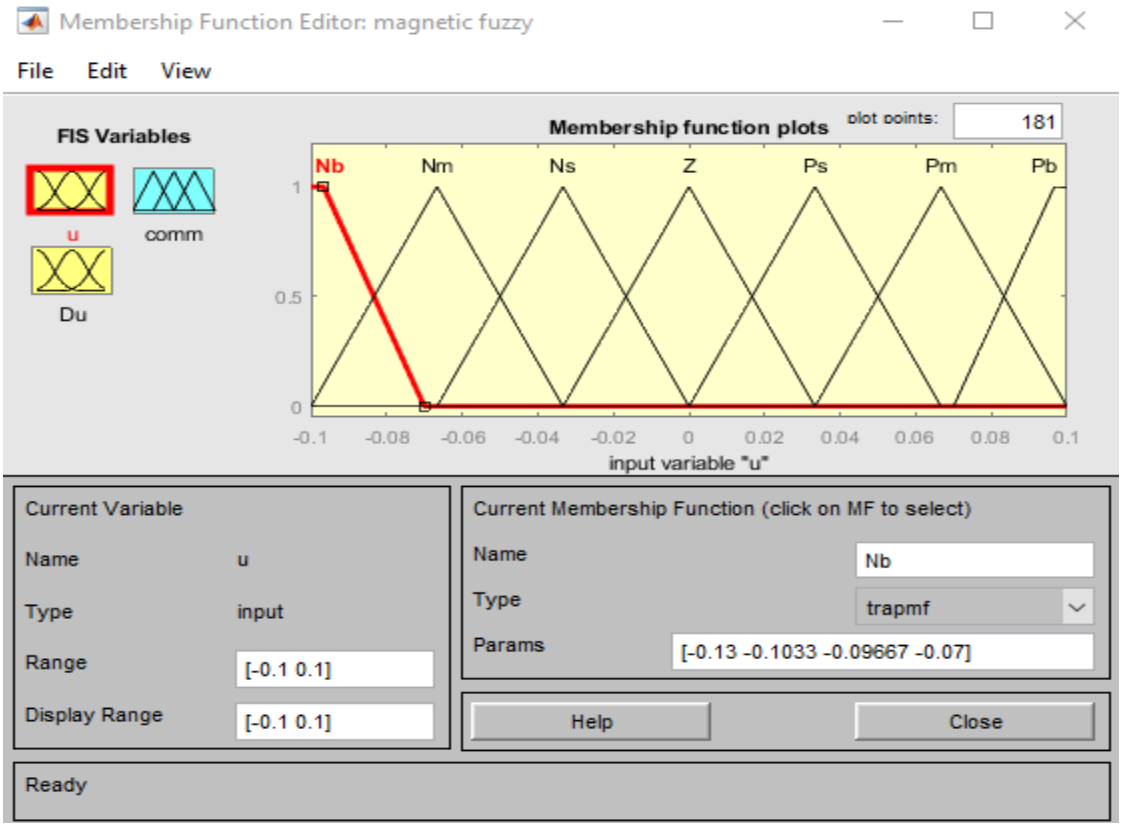


Fig4.12(a): Membership function ‘error’.

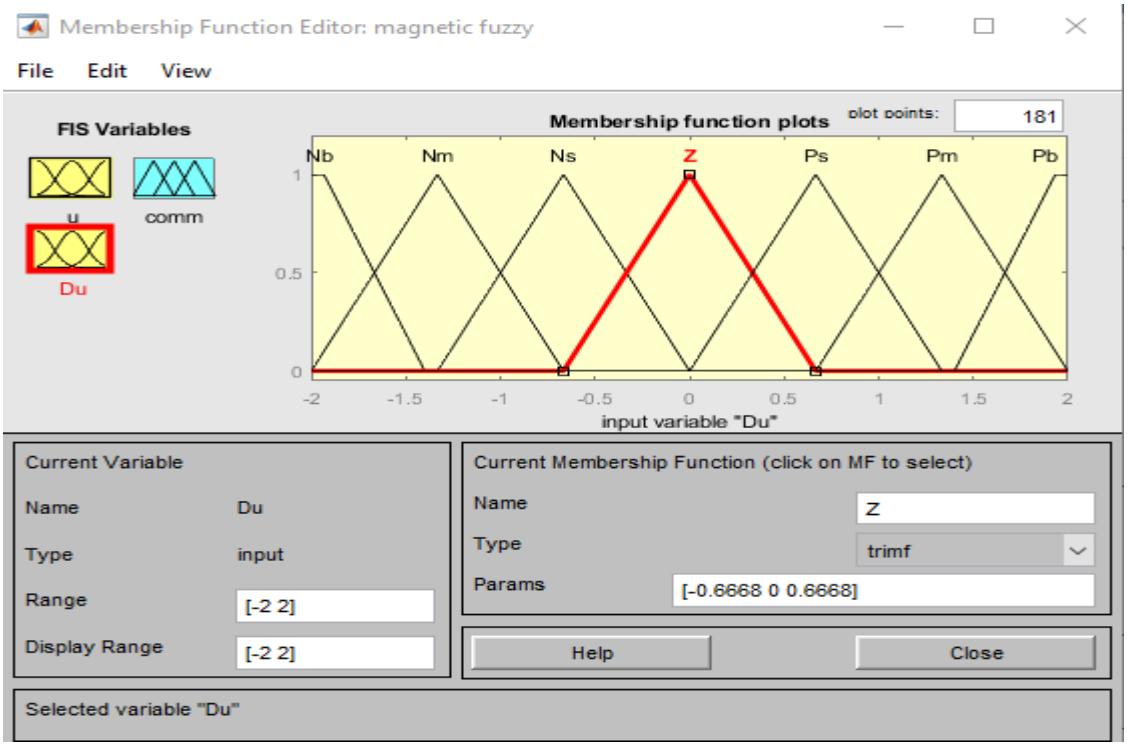


Fig4.12(b): Membership function ‘error’s derivative’.

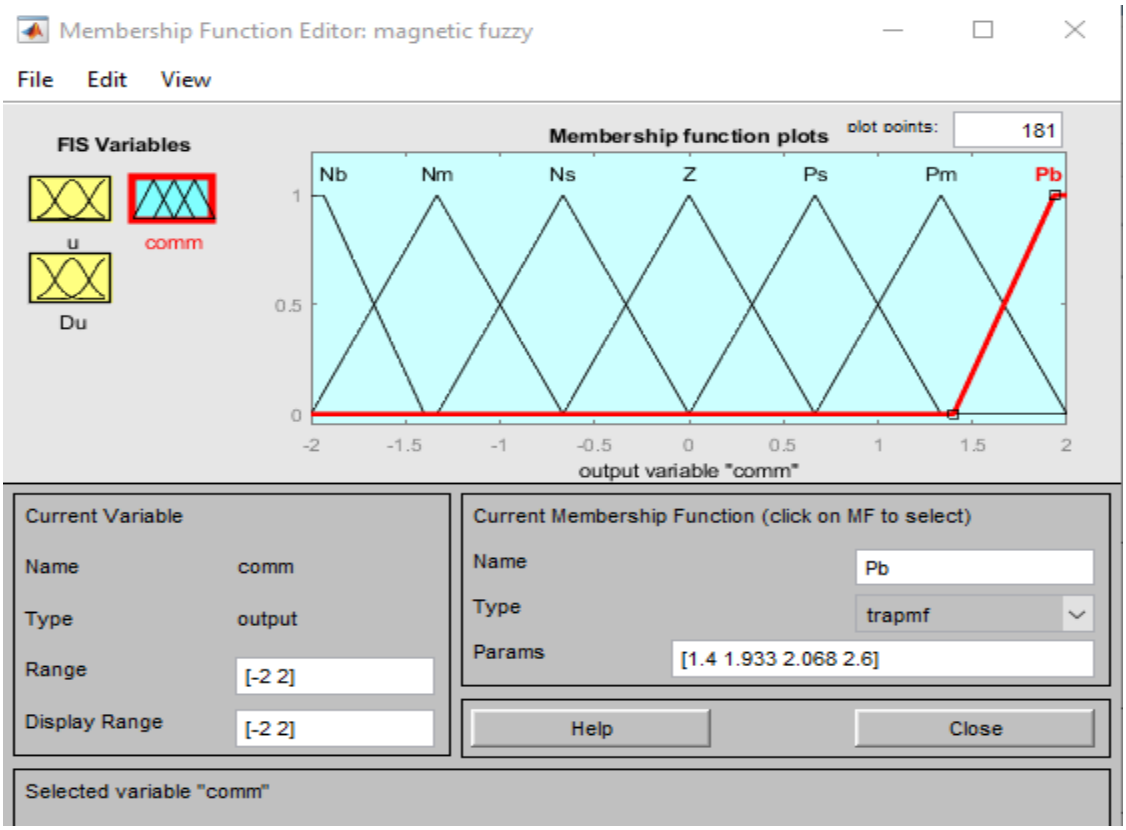


Fig4.12(c): Membership function ‘command’.

➢ Rules of inference:

the nember of rules of this system are 49 rules, Their summary is in the table01.

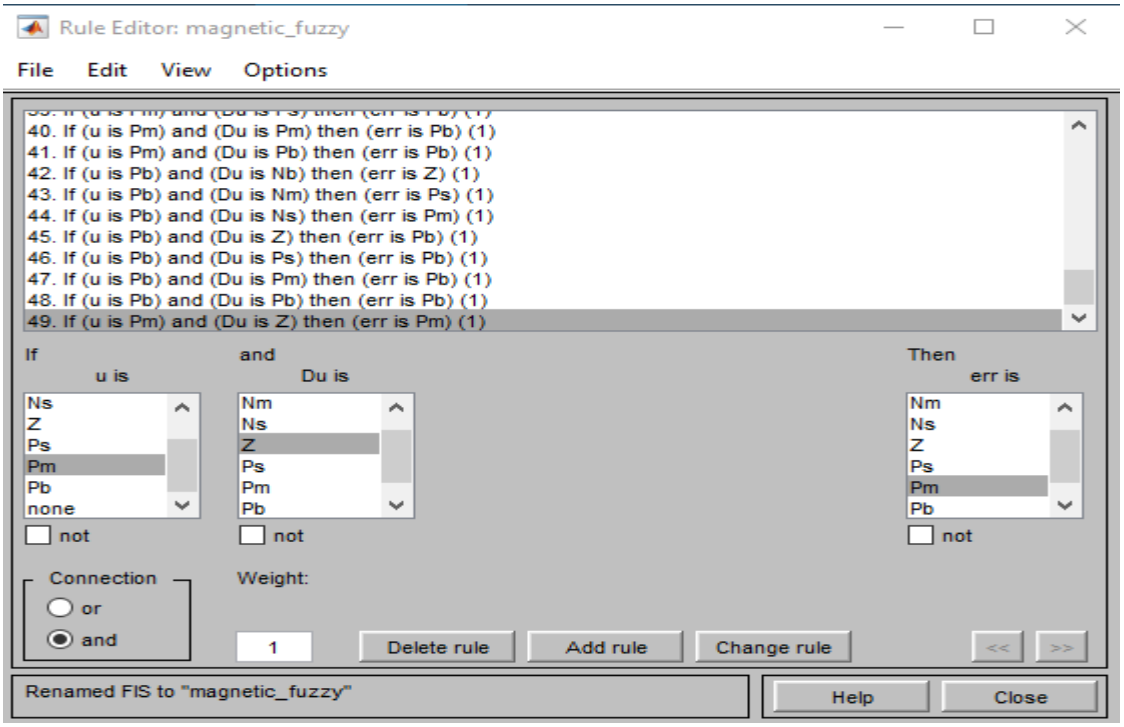


Fig4.13: Implementation of rules in the Matlab (fuzzy controller).

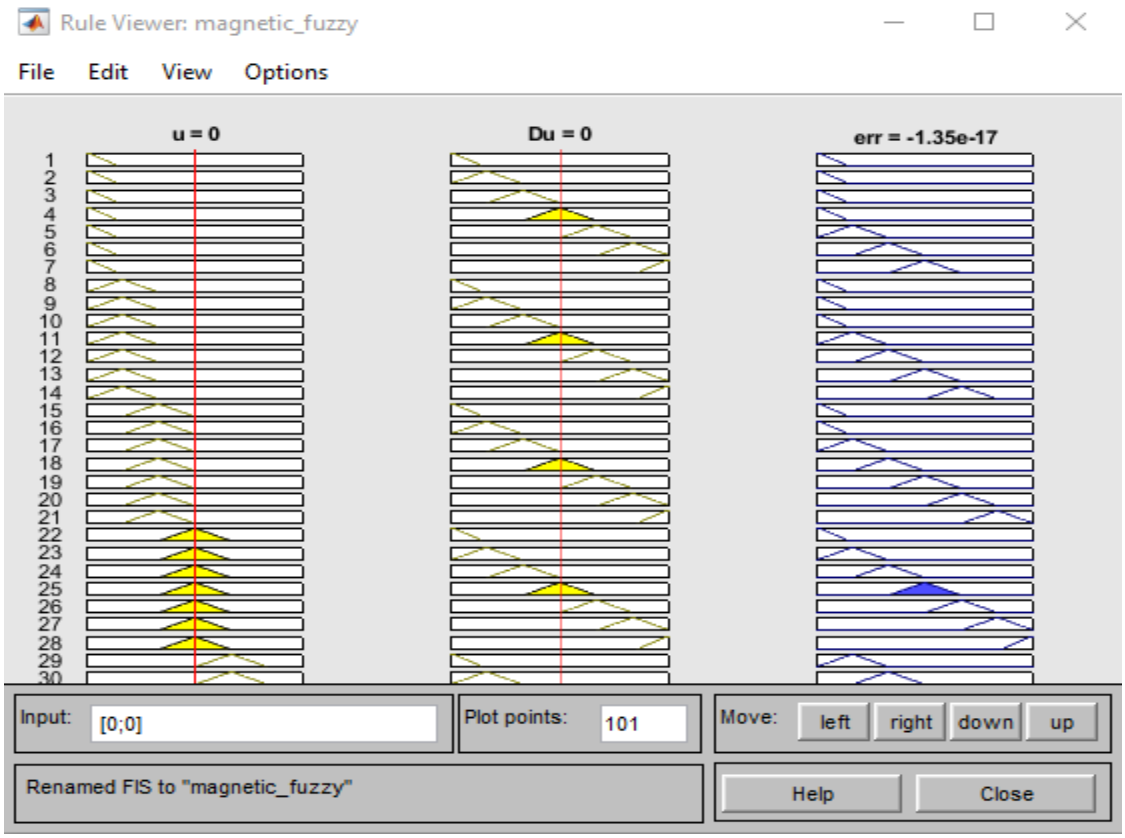


Fig4.14: Graphical representation of the rules.

➢ simulation results:

The position variation curve as a function of time shows that the system is stable after 0.28s. This is the time required for the flat moving part to return to the stationary state.

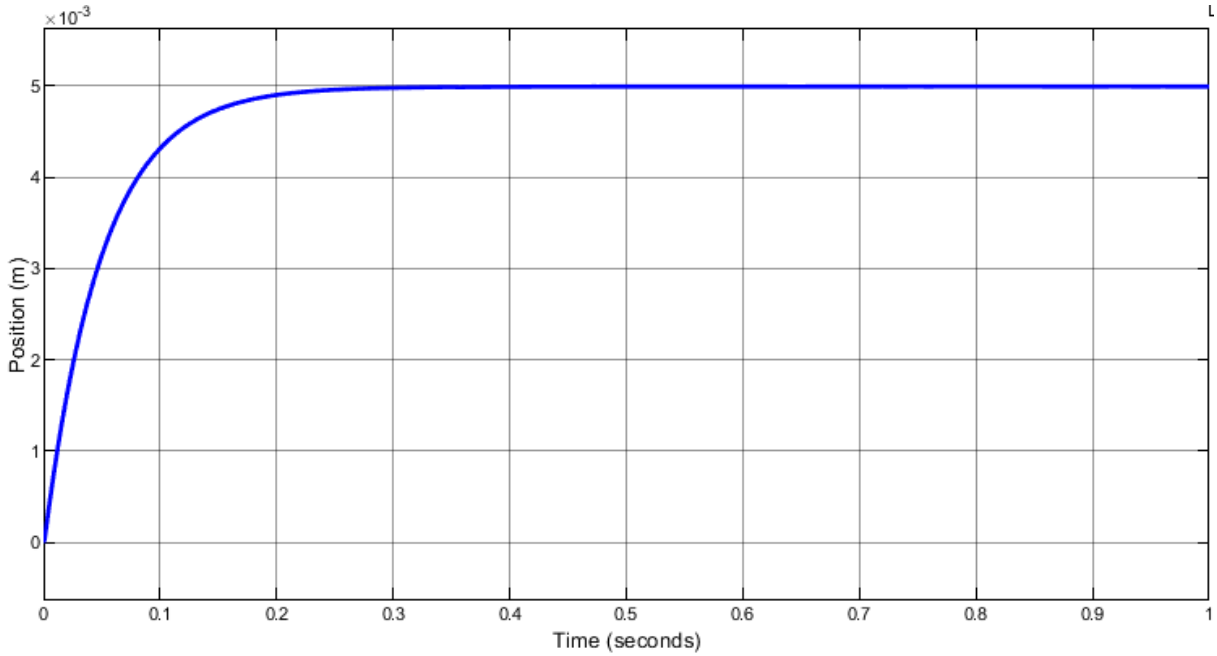


Fig4.15: System response for a desired position of 5×10^{-3}m by Fuzzy controller .

On its part, the electromagnetic force takes a stability value after the same time as those of the position. The force tends towards zero after this time, this is very logical because the latter is eliminated by the force of gravity during stability.

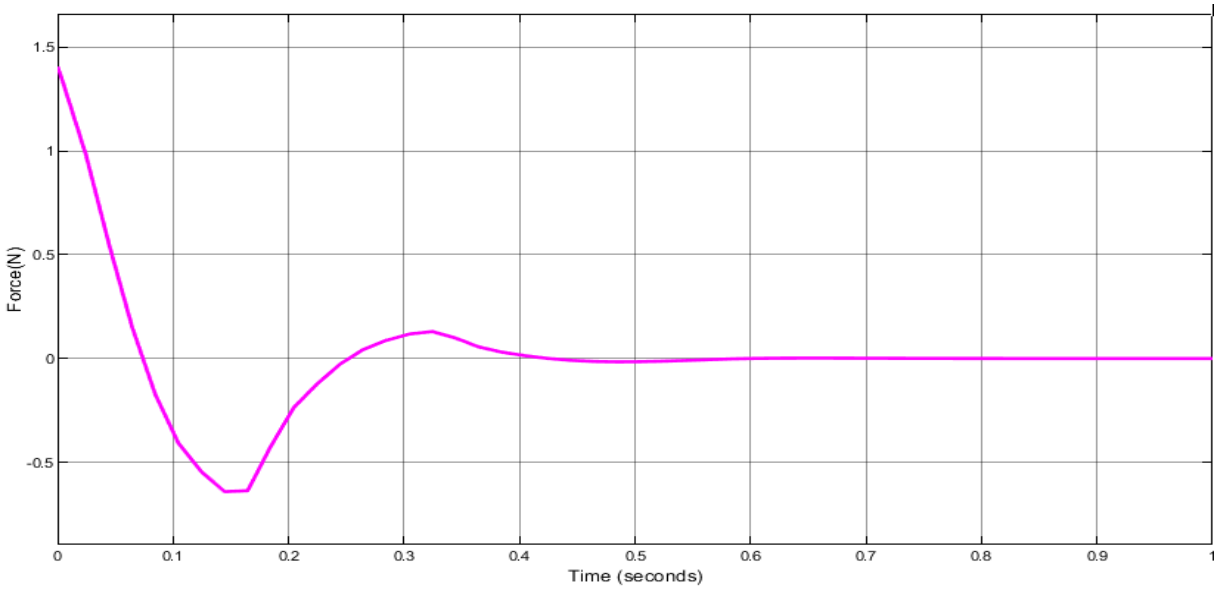


Fig4.15: The electromagnetic force of the system of control by a Fuzzy controller.

During the stability of the electromagnetic system we can clearly notice that the position error which is the difference between the reference position (setpoint) and the estimated value is zero, which confirms that the two values are equal.

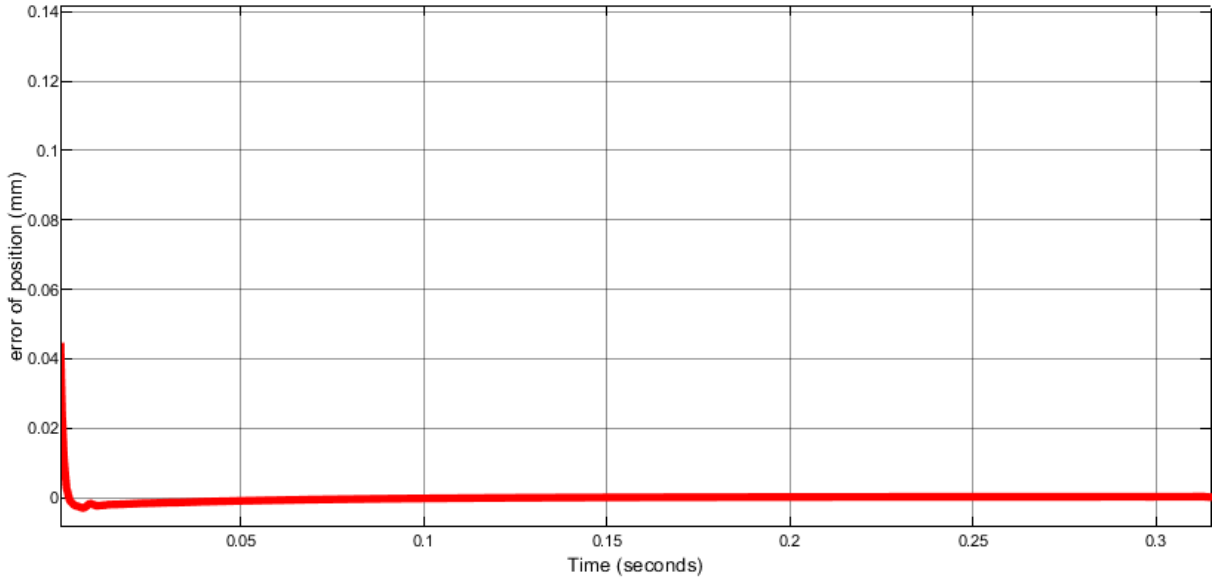


Fig4.16: The error between the reference position and the estimated by Fuzzy controller.

IV-5 The comparison between Controllers (PID,PD,Fuzzy logic):

To make the difference between the different controllers we work to realise the simulation of three controllers as it's presented here:

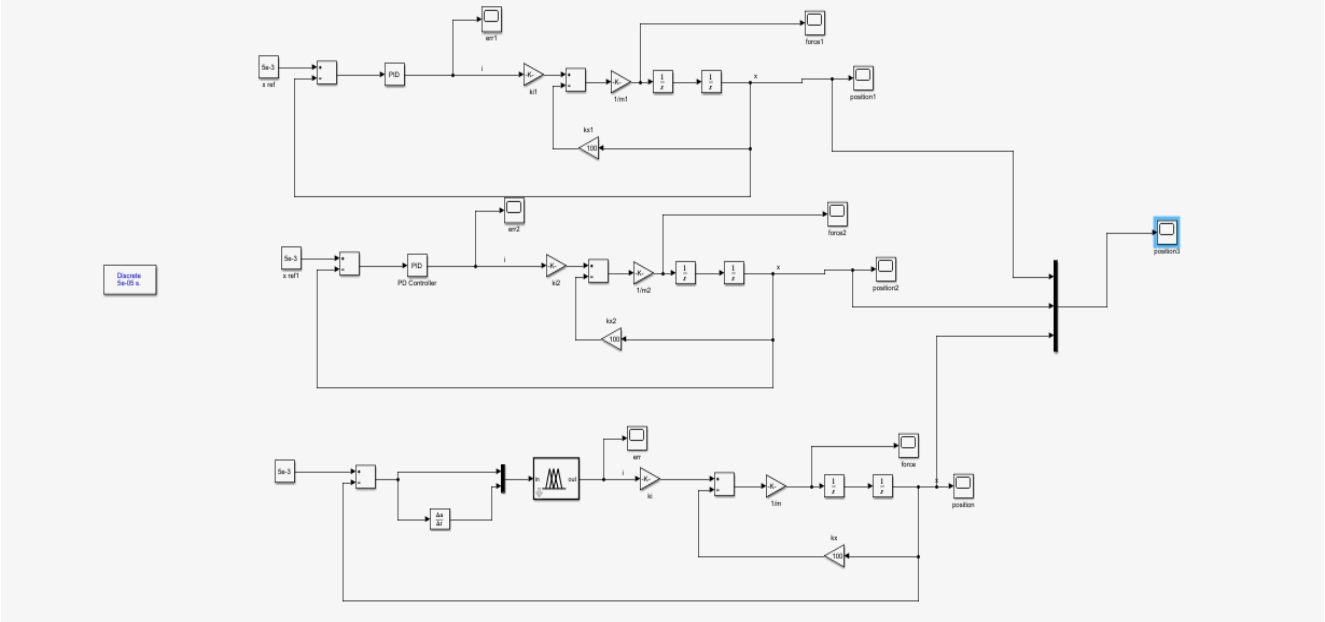


Fig4.17: The simulation of the comparison between controllers .

IV-5-1 The result

The best position is the one found by using fuzzy controller because it didn't consume long response time and there is no overshoot in it as well, then PD controller because it took long response time compared to fuzzy controller and finally PID controller is the worst result because it has both the overshoot and the long response time .

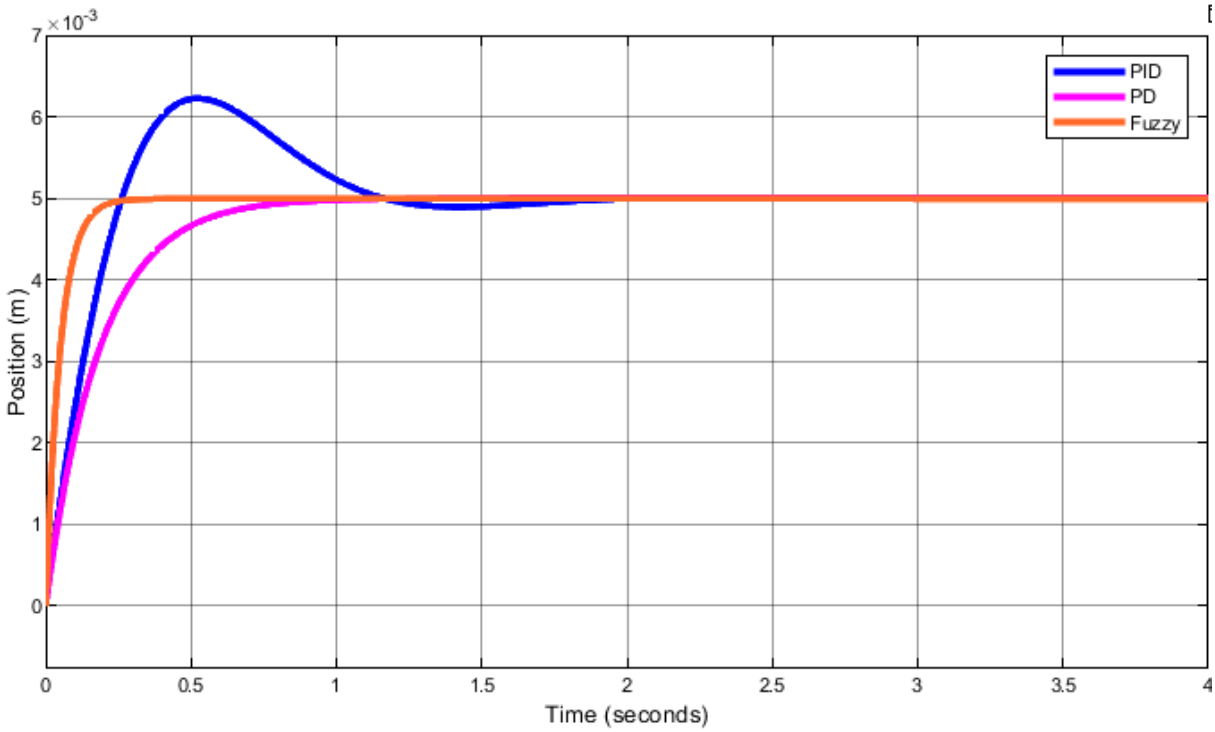


Fig4.18: the result of comparison.

IV-6.Conclusion:

In this chapter, we presented the results obtained for different control techniques of a planar magnetic bearing, and the comparison between them.

General Conclusion

In this work, we have explored the control and modeling of planar magnetic bearing (PMB) systems, which are fundamental to enabling contactless, high-precision, and high-speed motion in various industrial and research applications. PMBs offer numerous advantages over traditional mechanical bearings, including no physical contact, reduced friction and wear, minimal maintenance, and suitability for vacuum or harsh environments. However, they are inherently nonlinear and open-loop unstable, which makes effective control both challenging and essential.

We began by developing a mathematical and analytical model of the planar magnetic bearing, capturing its essential dynamic behavior and the nonlinear characteristics of the magnetic forces involved. This model provided a foundation for the design and evaluation of different control strategies. Throughout our study, we aimed to determine which controller—PID or Fuzzy Logic—would be more suitable for regulating the position and force in PMB systems.

We implemented and analyzed the PID controller, a classical and widely used control technique due to its simple structure and ease of tuning. The PID controller showed acceptable performance in regulating system behavior under nominal conditions and offered a relatively fast response. However, its lack of adaptability and sensitivity to system nonlinearities and disturbances became apparent, especially when the operating conditions changed or uncertainties were introduced.

To address these limitations, we designed and applied a Fuzzy Logic Controller (FLC). By using a rule-based approach that mimics human reasoning and does not require an exact mathematical model, the FLC proved to be more flexible and robust. It effectively handled the system's nonlinearities, adapted well to variations, and provided better stability, smoother control, and more accurate positioning compared to the PID controller.

To validate and compare these control strategies, we conducted a series of simulations based on our system model. We evaluated key performance indicators such as positioning error, response time, overshoot, stability, and control effort. The results clearly demonstrated that while the PID controller can serve as a baseline solution, the fuzzy logic controller offers superior overall performance, particularly in complex or uncertain operating environments.

Based on our findings, we conclude that fuzzy control is better suited for planar magnetic bearing systems, particularly where adaptability, robustness, and precise control are required. The fuzzy controller's ability to cope with nonlinear dynamics and disturbances makes it a promising candidate for advanced PMB applications, especially as system complexity and performance demands increase.

Looking forward, we see significant potential in extending this work by exploring hybrid control strategies (e.g., combining fuzzy logic with PID or adaptive methods), as well as integrating machine learning for real-time tuning and optimization. Additionally, the implementation of sensorless control, fault-tolerant mechanisms, and predictive maintenance algorithms could further enhance the reliability and intelligence of future PMB systems.

In summary, our work highlights the importance of advanced control design in magnetic levitation systems and confirms that intelligent controllers like fuzzy logic offer clear advantages over traditional methods for achieving stable, accurate, and efficient control of planar magnetic bearings.

This work not only underscores the importance of selecting an appropriate control strategy for PMB systems but also demonstrates the growing relevance of intelligent control techniques in modern engineering. The outcomes of this study pave the way for future research into hybrid control methods, machine learning-based optimization, and the integration of sensorless estimation and fault-tolerant designs, aiming to further improve the performance, efficiency, and resilience of planar magnetic bearing systems in next-generation applications.

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