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НАЦІОНАЛЬНИЙ АВІАЦІЙНИЙ УНІВЕРСИТЕТ
ФАКУЛЬТЕТ АЕРОНАВІГАЦІЇ, ЕЛЕКТРОНІКИ ТА ТЕЛЕКОМУНІКАЦІЙ
КАФЕДРА АЕРОКОСМІЧНИХ СИСТЕМ УПРАВЛІННЯ

ДОПУСТИТИ ДО ЗАХИСТУ

Завідувач кафедри

__________Юрій МЕЛЬНИК

«___»_____________2024 р.

КВАЛІФІКАЦІЙНА РОБОТА

(ПОЯСНЮВАЛЬНА ЗАПИСКА)
ВИПУСКНИКА ОСВІТНЬОГО СТУПЕНЯ «БАКАЛАВР»

Тема: «Система керування рукою робота-маніпулятора»

Виконавець: студент групи СУ-404______________Юлія ПАШКОВСЬКА

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Київ 2024

MINISTRY OF EDUCATION AND SCIENCE
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FACULTY OF AIR NAVIGATION, ELECTRONICS
AND TELECOMMUNICATIONSAEROSPACE CONTROL SYSTEMS
DEPARTMENT

APPROVED FOR DEFENCE

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“_____”__________2024

QUALIFICATION PAPER

(EXPLANATORY NOTE)

FOR THE ACADEMIC DEGREE OF
BACHELOR

Title: **“**Control System of Robot Arm”

Submitted by: student of group CS-404 Yulia PASHKOVSKA

Supervisor: PhD, associate professor____________________Antonina KLIPA

Standards inspector:_________________________Mykola DYVNYCH

Kyiv 2024

НАЦІОНАЛЬНИЙ АВІАЦІЙНИЙ УНІВЕРСИТЕТ

Факультет аеронавігації, електроніки та телекомунікацій

Кафедра аерокосмічних систем управління
Спеціальність: 151 Автоматизація та комп'ютерно-інтегровані технології

ЗАТВЕРДЖУЮ

Завідувач кафедри

________Юрій МЕЛЬНИК

«__»_________2024 р.

ЗАВДАННЯ

на виконання кваліфікаційної роботи

Пашковської Юлії Олександрівни

1. Тема кваліфікаційної роботи «Система керування рукою робота-маніпулятора» затверджена наказом ректора від «01» квітня 2024 р. № 511/ст.
2. Термін виконання роботи: з 13.05.2024 по 13.06.2024.
3. Вихідні дані роботи: аналіз некомпенсованої системи, визначити її передатну функцію, стійкість та показники ефективності. Синтезувати PD- регулятор для досягнення бажаного фазового зсуву, оцінка стійкості і продуктивності компенсованої системи.
4. Зміст пояснювальної записки: Теорія робототехніки та поставновка задачі, Контролери для динамічних систем та їх проектування, Проектування системи керування рукою робота, Висновок, Список використаної літератури та ресурсів, Додаток.
5. Перелік обов’язкового ілюстративного матеріалу: Полюсно-нульова карта системи, Поля некомпенсованої та компенсованої розімкнутої системи,

Діаграма Боде для PD-регулятора, Часові характеристики некомпенсованої та компенсованої систем

6. Календарний план-графік

№ пор.	Завдання	Термін виконання	Відмітка про виконання
1	Огляд літературних джерел, знайомство з об'єктом	13.05.2024-17.05.2024	
2	Теорія робототехніки та поставновка задачі	18.05.2024-19.05.2024	
3	Контролери для динамічних систем та їх проектування	21.05.2024-23.05.2024	
4	Проектування системи керування рукою робота	25.05.2024-28.05.2024	
5	Висновок, підведення підсумків	30.05.2024-31.05.2024	
6	Оформлення пояснювальної записки	31.05.2024-01.06.2024	
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Керівник кваліфікаційної роботи ____________________ Антоніна КЛІПА
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Завдання прийняв до виконання ___________________Юлія ПАШКОВСЬКА
(підпис випускника)

NATIONAL AVIATION UNIVERSITY

Faculty of Air Navigation, Electronics and Telecommunications
Aerospace Control Systems Department
Specialty: 151 “Automation and Computer-integrated Technologies”

APPROVED BY
Head of the Department
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«___»________2024 р

Qualification Paper Assignment for Graduate Student

Pashkovska Yulia Oleksandrivna

1. The qualification paper title “ Control System of Robot Arm ” was approved by the Rector’s order of “ 01 ” April2024 № 511/ст.
2. The paper to be completed between: 13.05.2024 and 13.06.2024
3. Initial data for the paper: analyze the given uncompensated continuous system to determine its transfer function, stability, and performance metrics. Synthesize a PD-compensator to achieve a desired phase margin, then evaluate the compensated system's stability and performance.
4. The content of the explanatory note: Theory of robotics and problem statement, Controllers for dynamic systems and their design, Designing of control system for robot arm, Conclusion, References, Appendix
5. The list of mandatory illustrations: Pole-zero map of the system, Margins of uncompensated and compensated open-loop system, Bode Diagram PD controller, Time responses of uncompensated and compensated systems

6.Timetable

№	Assignment	Dates of completion	Completion mark
1	Overview of the existing system and its components	13.05.2024-17.05.2024	
2	Theory of robotics and problem statement	18.05.2024-19.05.2024	
3	Controllers for dynamic systems and their design	21.05.2024-23.05.2024	
4	Designing a robot arm control system	25.05.2024-28.05.2024	
5	Conclusion, summing up the results	30.05.2024-31.05.2024	
6	Preparation of an explanatory note	31.05.2024-01.06.2024	
7	Preparing a presentation	01.06.2024-10.06.2024	

6. Assignment issue date: “13” May 2024

Qualification paper supervisor ____________________Antonina KLIPA
(the supervisor’s signature)

Issued task accepted ____________________Yulia PASHKOVSKA
(the graduate student’s signature)

РЕФЕРАТ

Пояснювальна записка до дипломної роботи «Система керування рукою робота-маніпулятора» містить 53 сторінки, 20 рисунків, 3 таблиці, 10 літературних джерела.

Актуальність теми полягає в тому, що вона відіграє ключову роль у розвитку робототехніки, задовольняючи потребу в оптимізованих стратегіях управління для забезпечення точності, ефективності та безпеки роботи маніпуляторів роботів у різних сферах застосування, тим самим стимулюючи прогрес в автоматизації та підвищуючи продуктивність праці в промисловості.

Об'єктом дослідження є проектування та аналіз систем керування руки робота маніпулятора з акцентом на методі налаштування ПІД-регуляторів.

Предметом дослідження є рука робота маніпулятора

Метою роботи є створення робочої моделі руки робота маніпулятора, що забезпечує автономну роботу та придатність для комерційного використання.

Методи дослідження: методи аналізу стійкості, методи запасів стійкості за амплітудою, методи синтезу ПІД-регуляторів: діаграма Ніколса.

Ключові слова: PD-РЕГУЛЯТОР, СИНТЕЗ КЕРУВАННЯ, СИСТЕМА КЕРУВАННЯ, РУКА-РОБОТА МАНІПУЛЯТОРА.

ABSTRACT

Explanatory note to the diploma work ‘Control System of Robot Arm’ contains 53 pages, 20 figures, 3 tables, 10 references.

The relevance of the topic lies in the fact that it plays a key role in the development of robotics, meeting the need for optimised control strategies to ensure the accuracy, efficiency and safety of robot manipulators in various applications, thereby stimulating progress in automation and increasing productivity in industry.

The object of study is the design and analysis of robot arm control systems with an emphasis on PID tuning methods.

The subject of research is the robot arm.

The aim of the work is to create a working model of a robot arm that provides autonomous operation and suitability for commercial use.

Research methods: methods of stability analysis, methods of stability margins by amplitude, methods of synthesis of PID controllers: Nichols diagram.

Key words: PD-CONTROLLER, CONTROL SYNTHESIS, CONTROL SYSTEM, ROBOT ARM.

CONTENT

INTRODUCTION

Currently, the field of robotics is actively developing: new robot models are regularly created and already created robot models are produced.

First of all, we are talking about the production of industrial robots that can significantly facilitate and accelerate the production process in any field of activity. Their application is not limited only to the sphere of production. Military and security companies actively use robots for perimeter protection, as well as for such a dangerous for human life and health activity as minefield clearance. Robots are also used in astronautics as explorers of other planetary systems.

The development of robots is not limited to the creation of a simple artificial intelligence to execute simple commands. The creation of neural networks is actively developing, which can significantly increase the potential of robots in areas where non-standard solutions and creativity are required.

It should also be said that robots are capable of exchanging information with each other or transferring data to a personal computer, providing humans with the necessary information.

The modern level of robotics development allows robots to be equipped with a wide range of additional equipment such as cameras, navigation systems, motion, light, sound, etc. All this allows to significantly expand the capabilities of robots and thereby expand their application area.

With the formation of robotics, three types of robots were defined: with a rigid program of actions; manipulators, controlled by a human operator; with artificial intelligence (in some cases called in-tegral), functioning purposefully (“intelligently”) without human intervention. Most of today's robots (absolutely all three types) are robot manipulators.

Industrial robot manipulator contains a “mechanical arm” (one or several) and a remote control panel or a built-in program control device, less often an electronic computer.

Manipulator - a complex of spatial lever mechanism and concept of drives, performing under the control of a programmable automatic device or a human operator impacts (manipulations), similar to the operations of the human hand. Industrial robots are designed to replace humans. In this case, an important social goal is solved - to relieve a person from work involving health hazards or heavy physical labor, as well as from simple monotonous actions that do not require significant qualifications.

Elastic automated production formed on the basis of industrial robots makes it possible to solve automation problems at enterprises with a wide range of products in small batch and piece production. Computer modeling of robotic concepts has an enormous role in the fields of science and technology. A large number of time-consuming physical work of human beings has been replaced by robots today, and computer devices, computer mathematics systems have greatly facilitated massive calculations and transformations, reducing them to a minimum. Computer models are used to extract new insights about the object being modeled or to approximate the behavior of mathematical systems that are very difficult to investigate analytically. Computer modeling is considered one because of, financial or physical obstacles, or may provide an unforeseen outcome.

The relevance of the choice of the basis and use of interactive manipulator is determined by the following: the use of information and communication technologies in educational activities; increasing the effectiveness and efficiency of the educational process, the need to develop a new type of student - a competent user of information educational services.

The purpose of diploma is to research the system of automatic control system of robot arm.

The first chapter will describe the theory of robotics and my problem statement, you see the main elements and characteristics of robot arm. The robot arm assembled as part of this thesis project will be demonstrated and its characteristics will be described.

The second chapter will describe the controllers for dynamic systems and their design, which types of controllers used with dynamic systems, PID controller structure and its influence on a dynamic system, tuning of PID-controller coefficients by the step response method and tuning of PID-controller coefficients by the frequency response method.

In the third chapter, the design of the robot arm control system will be analyzed, synthesizing a real PD-compensator which would provide a desired phase margin at a given gain crossover frequency and analyzing a compensated system.

In conclusion the main results obtained are given, the work done is summarized.

CHAPTER 1.
THEORY OF ROBOTICS AND PROBLEM STATEMENT

1.1.Theory of robotics

By now, technological advances have led to the creation of robotics and the emergence of robots programmed to perform tasks.

This has had a particularly strong impact on manufacturing industries. In any modern factory, it is the robots that do the bulk of the work. This has reduced the labor intensity as well as the cost of production.

Robots are capable of performing monotonous work, the efficiency of which does not decrease during long hours of labor. In addition, in some cases, a robot is able to perform work that is impossible for humans, for example, carrying heavy objects such as multi-ton containers or steel beams. In addition to this, robots are many times more efficient and safer than humans for the tasks of exploring the Moon and Mars or clearing minefields due to their greater resistance to aggressive environments and damage.

A robot is an automatic device that is programmed to execution of a given action.

The main elements of a robot are:

1) Frame - this is the base of the robot, which holds the entire structure together.

2) Power - any suitable source of energy required for performance.

3) Microcontroller is an electronic control device.

It is a less powerful version of a microprocessor with memory, I/O devices, timers, etc.

4) An actuator, in particular motors, devices for it converts electrical or any other energy into mechanical energy.

5) Sensors - sensitive elements that transmit information about the external environment to the controller. They are especially important for mobile robots, allowing them to identify and bypass or remove an obstacle in the path of movement with the help of a manipulator [1].

The main three characteristics of a robot are: degree of freedom, load capacity and accuracy.

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Submitted	Pashkovska Y.O.			CHAPTER 1 THEORY OF ROBOTICS AND PROBLEM STATEMENT		Sheet	Sheets
by Supervisor	Klipa A.M.					14	53
St Inspector.	Dyvnych M.P.				CS-404		
Head of Dep	Melnyk Yu.V.						

1) Degree of freedom is the number of independent variables that are uniquely responsible for the mobility of the robot. Often the degree of freedom of a robot depends on the number of motors. The number of motors is the number of degrees of freedom. For example, the robot assembled in this diploma project has three motors: one motor is directly responsible for the manipulator arm, the other two motors are responsible for the rear and front drives of the robot, allowing it to move.
2) The payload capacity determines the maximum mass that the robot the robot is capable of lifting.
3) Accuracy characterizes the performance of a given action with the smallest possible error.

Special precision requirements apply to robots that perform extremely fine work, where a small inaccuracy can seriously affect the quality of the final product. For example, a forklift robot is not afraid to place the container to be carried a couple of centimeters to the left of the desired point. Whereas a robot responsible for installing resistors on a printed circuit board, having missed by a couple of centimeters, can simply ruin both the board and the resistors.

All of the above means that a robot is required to perform a range of complex tasks. A whole range of complex tasks: Motion Control Problem.

For non-stationary robots, it is necessary to ensure its mobility, as well as to control the manipulators and sensors.

1) Navigation task - it is required to know in real time the current position of both the robot in space and its individual elements (the same manipulators and sensors).
2) The task of motion planning - programming the robot to move along a certain path, perform the necessary maneuvers to avoid obstacles, as well as possible correction of the path of movement and control of the accuracy of movement.
3) The task of stable communication channel - it is necessary to ensure continuous communication between the computer installed on the robot and the remote terminal through which the control is carried out.
4) The task of recognizing the environment is to provide the robot with sensors to recognize obstacles on the path of movement or to determine the necessary object for interaction [2].
5) It should also be remembered that when implementing robots, it is required to provide them with the highest possible performance to improve the efficiency of real-time operation. However, it should be taken into account that an excessive increase in speed may negatively affect both the reliability of this system and its cost.

1.2.Control system of robot arm as an object of research

Nowadays, there are many different designs of manipulator like human hand. They have found a wide range of applications in life for prosthetics, controlling various machines and moving objects.

Research into new prosthetic devices that can be connected to human neural networks and controlled by brain signals. In the near future, it is possible that very soon mechanical arms and legs with a neural interface will simplify the lives of many people with missing limbs (Figure 1.2.1).

In addition, exercises with such devices are an effective way to rehabilitate patients paralyzed by disease or injury. After all, by sending mental signals to special manipulators, they learn to control their own bodies again.

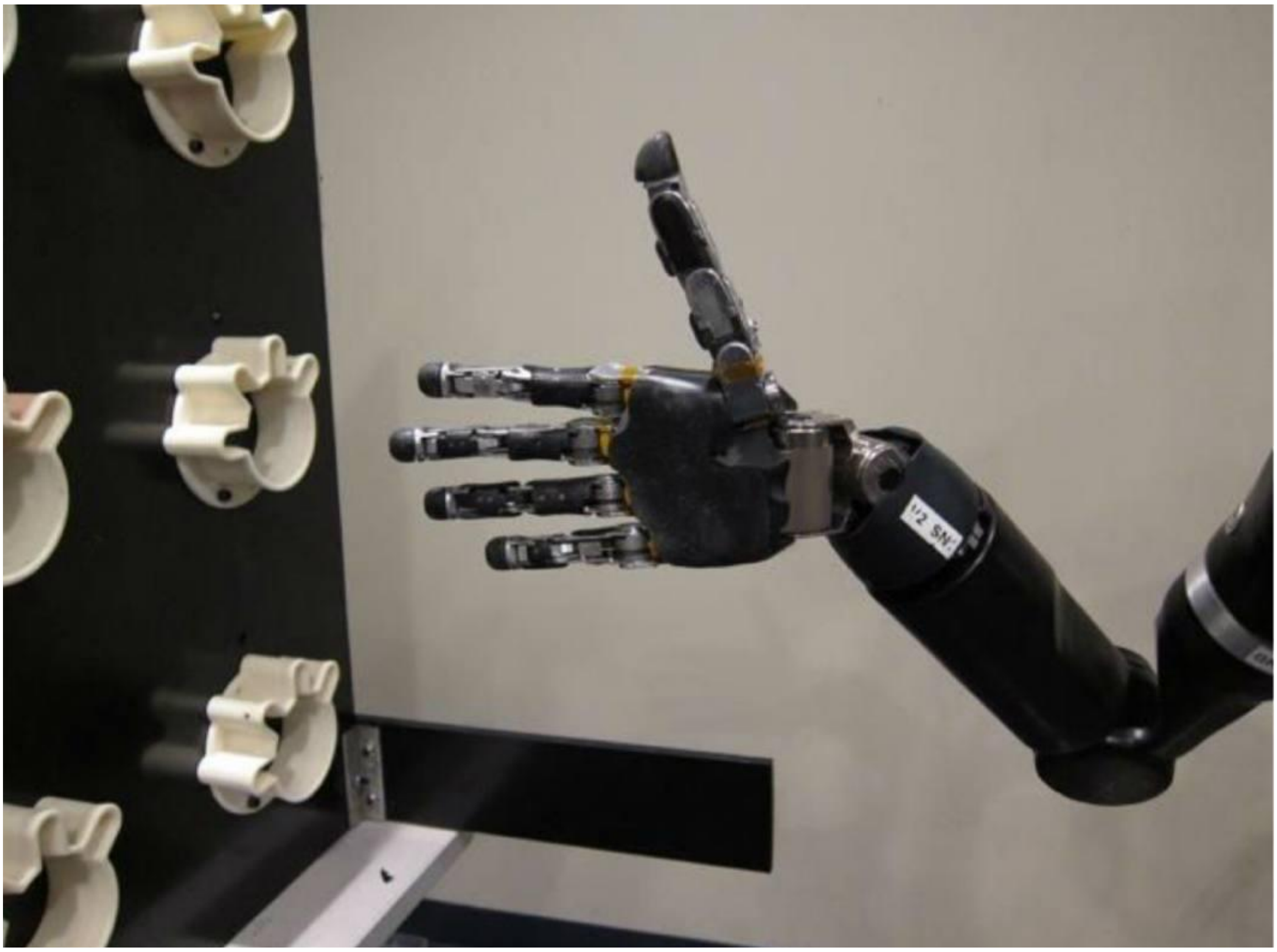

Fig.1.2.1.New manipulator with neural interface has ten degrees of freedom (photo by Journal of Neural Engineering)

An example of the movements and capabilities of the manipulator with neural interfaces is shown below in Figure 1.2.2.

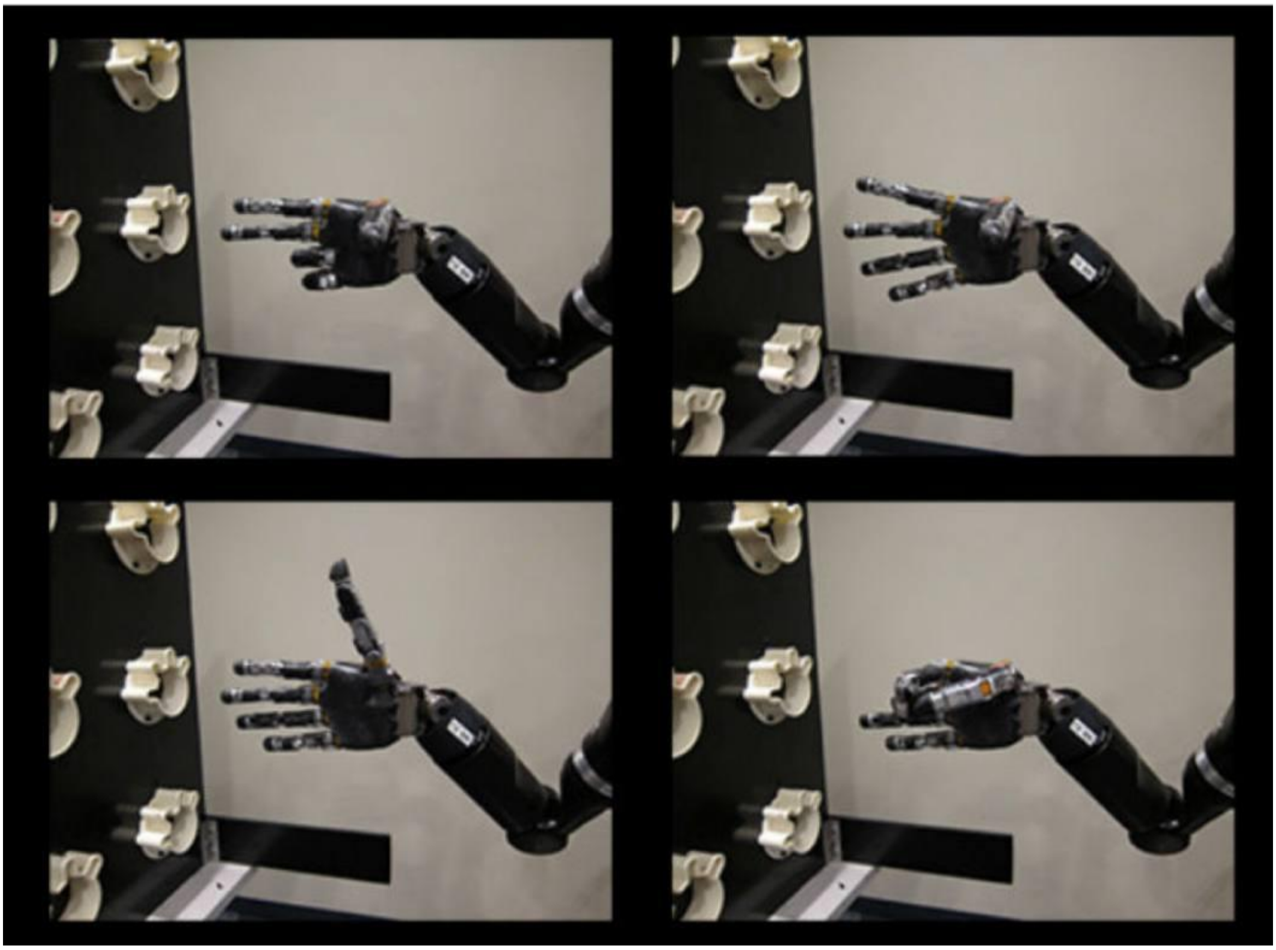

Figure 1.2.2. Demonstration of the capabilities of a manipulator with a neural interface (photo by Journal of Neural Engineering)

A manipulation robot is a reprogrammable multifunctional manipulator designed to perform certain predetermined movements of materials, parts, tools or special devices in order to perform various works. The most important component of a manipulation robot is the manipulator itself - a device for performing motor functions similar to those of a human hand when moving objects in space, equipped with a working organ. By its structure, the manipulator is a multilink machine, between the individual elements of which there are mechanical links. Most of the currently existing manipulation robots use electric motors to perform movements. The basic structure of the “arm” is a sequence of links connected by rotational and translational links.

This diploma project considers the task of control system of Robot Arm. Similar systems controls are characterized by high requirements for accurate management.

This imposes special requirements to the synthesis is automatic management systems.

Figure 1.2.3 shows a diagram of the robot hand. As you can see, it consists of two parts: a control device that consists of a program control and manipulator control systems and the manipulator.

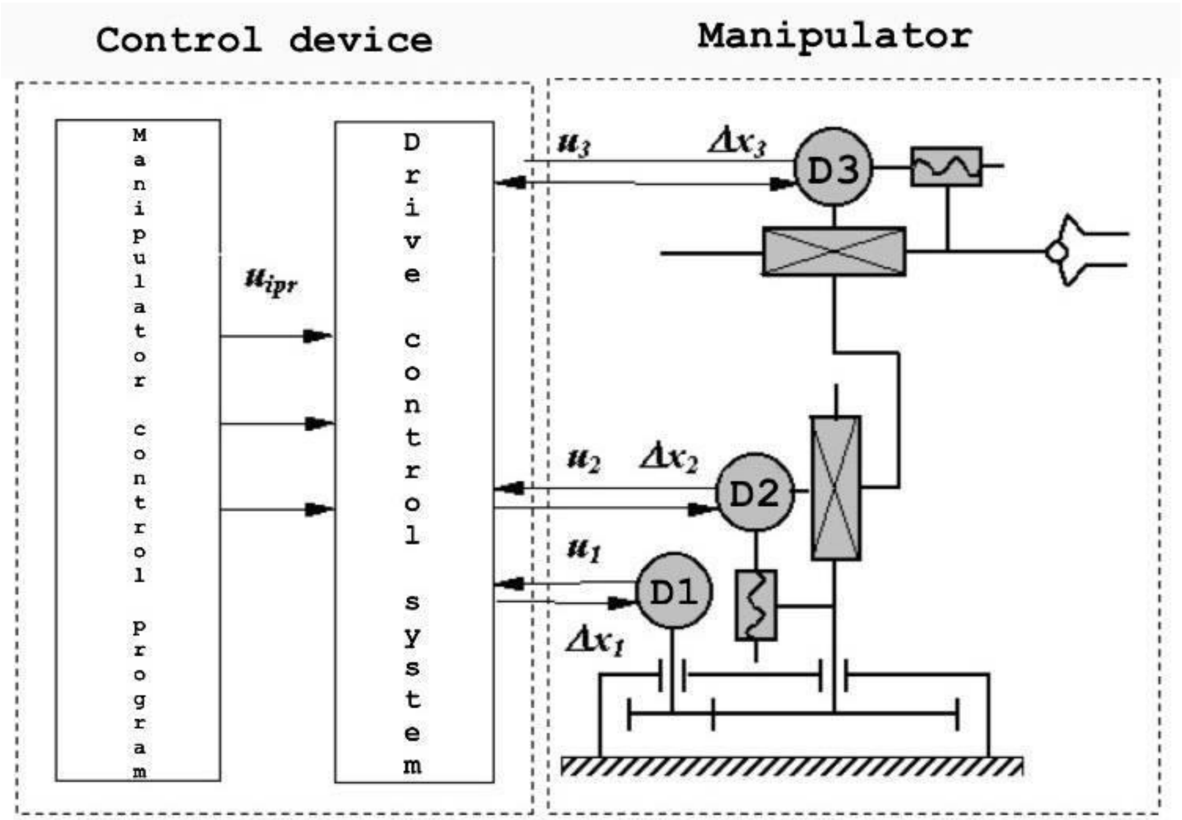

Fig.1.2.3. the scheme of Robot arm

In general, the robot control system itself consists of external equipment and software device, a control unit, instrumentation and internal information sensors.

The design of the control system is shown on Figure 1.2.4.

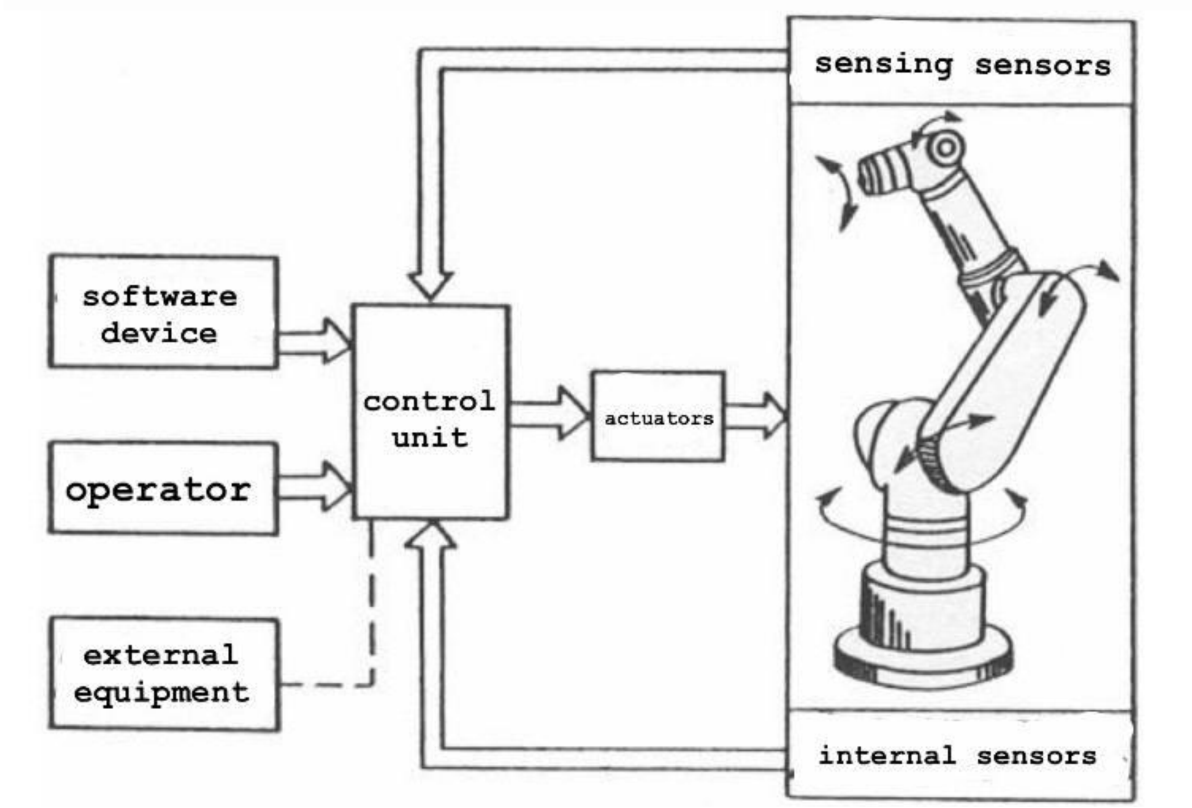

Fig. 1.2.4. Robot control system

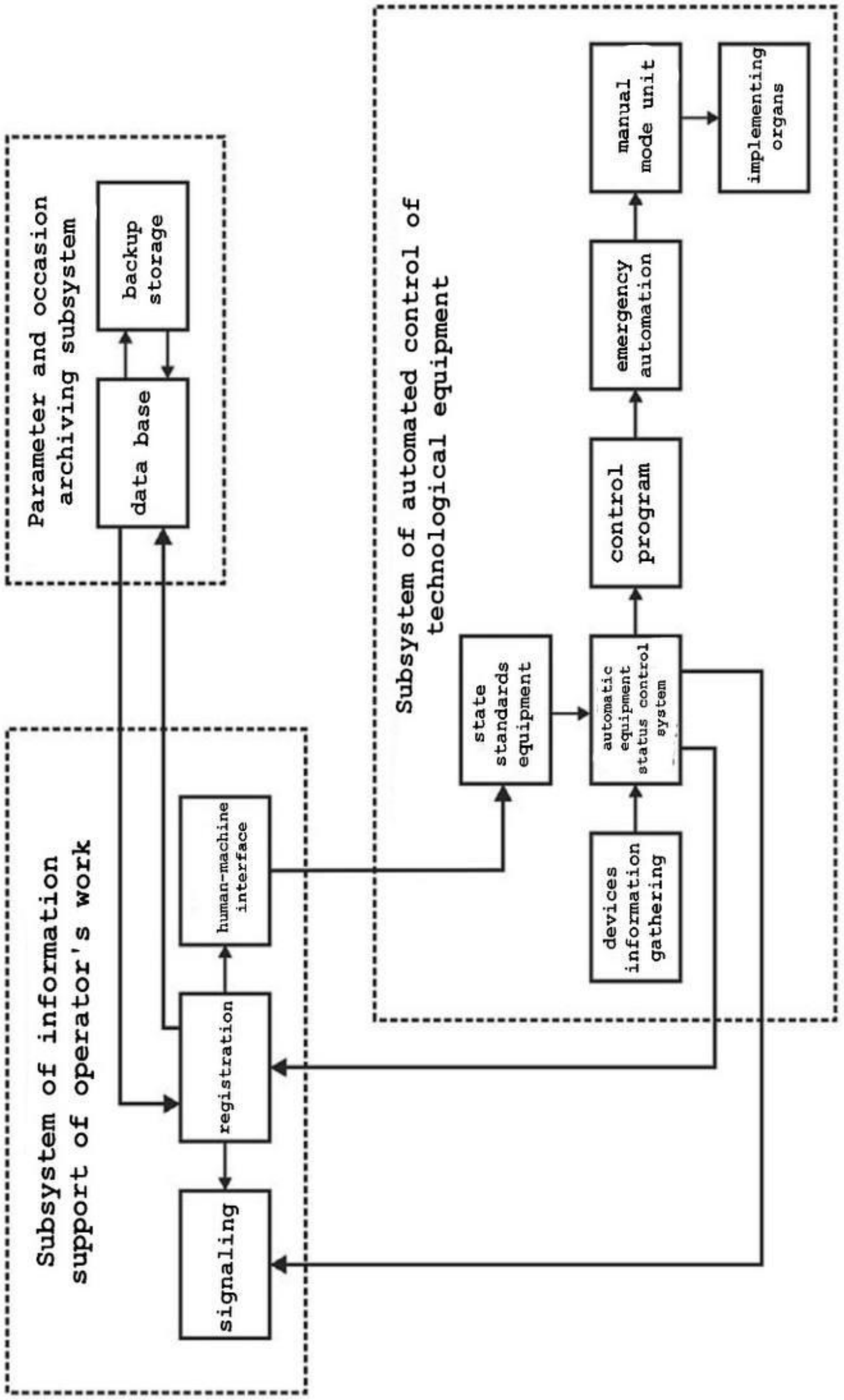

Fig.1.2.5. Functional diagram

Figure 1.2.6 shows a schematic of the automation of the robot arm, with the devices installed locally, on the local console and on the panel.

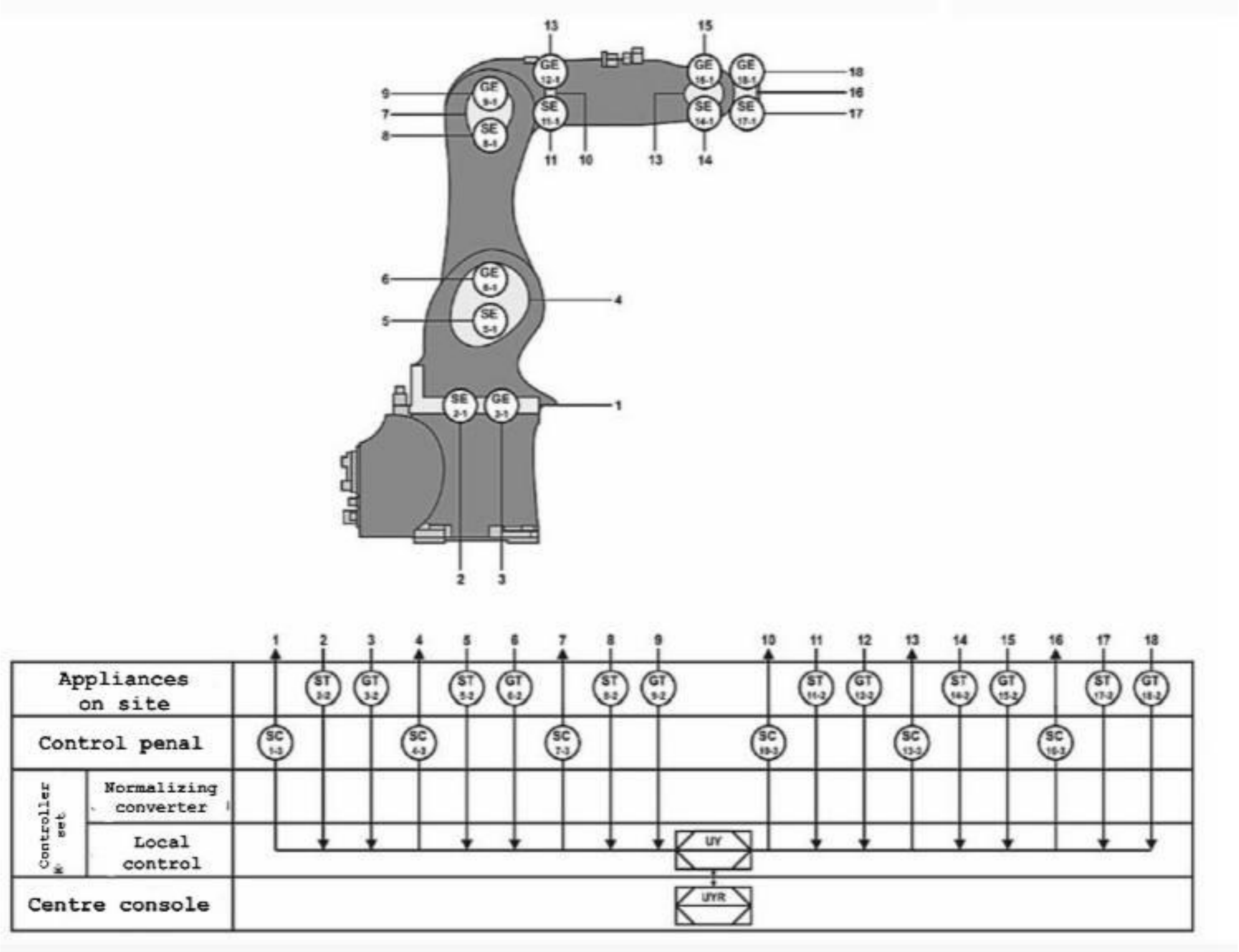

Fig.1.2.6. Robot automation scheme

A robot is an automatic machine that consists of a manipulator and a device for programmatically controlling its movement.

Robots are used to perform primary or some secondary to work in place of a human being.

A manipulator is a combination of a spatial lever mechanism and an actuator system that performs under the control of a programmable an automatic device or a human operator to perform actions (manipulation) similar to the actions of a human hand.

Figure 1.2.7 shows an industrial robot manipulator. Robots designed to replace a human being in the performance of basic and auxiliary tasks. In doing so, the human is freed from the need to To perform laborious and monotonous work, the use of robots reduces the risk of injury.


Fig.1.2.7. Industrial Robot Arm

Each robot performs a different range of tasks. A painting robot is responsible for applying compounds to the surface, while the manipulator robot performs the tasks of movement is performed by the robot arm. This "division of duties", firstly, simplifies the design, and secondly, increases the reliability of the system, because the simpler the program given to the robot, the less the risk of failures. There is less risk of malfunctions. The different types of the tasks performed by the robots:

1) Manufacturing of parts. There are widespread use of machines for forging, cutting and casting. A workpiece is loaded into an industrial machine where it is processed according to a predetermined algorithm. It is processed according to a predetermined algorithm. The finished the workpiece is extracted by workers or, if the dimensions do not allow it to be extracted manually, it is done by a robot programmed to extract the workpiece and its subsequent transfer to the next production stage.

2) Moving. Heavy containers and heavy objects stored in warehouses must be transported. Either to the production facility, or to the logistics department for transportation. Again, due to the large size of the objects to be moved, the use of manpower for this operation traumatic and inefficient.

3) Loading and unloading heavy objects. The task of loading heavy objects is particularly relevant for heavy industry plants to moving heavy objects from one conveyor to another. These robots usually do not have a moving chassis for unnecessary

reasons, and the robot is a stationary unit fixed between two production lines.

4) Packaging. The finished product must be packaged to protect it from external influences. Such robots wrap the products, usually in a polyethylene film protecting it from moisture and dust, after which it is packed in a container (box, crate, case), protecting from mechanical damage during transportation.

5) Processing of parts and blanks. These robots are well proved themselves in the manufacture of metal and wooden workpieces by machining the original part.

6) Finishing. Removal of irregularities from the workpiece, roughness and various burrs. This operation is one of the most difficult to accomplish in terms of automation. The problem is that robots, unlike humans, don't have the ability to evaluate their own of the work. The robot can't tell for itself if a part is cleaned well enough or not.

7) Drilling. For this kind of work, a robot is used, the actuator of which is a drill or a perforator. The use of such robots are justified when it is necessary to carry out a large number of holes or the size of the required holes compel the use of large-sized tools. This is especially true in airplane construction, as large aircraft parts need to make a large number of holes with which they are joined together.

8) Application of various compositions on the surface. The application of glue to the part for further connection with another part, painting, treatment with a special compound that enhances the performance of the part. The efficiency of robotic painters is higher than that of human painters because the compound is applied evenly over the entire surface of the workpiece. Often these robots are equipped with means of protection against the aforementioned compositions. This is accomplished by either installing a protective screen or by the robot is programmed to perform periodic self-cleaning. The workpiece is protected from possible spillage of compounds.

10) Welding. Often used in mechanical engineering, robot welders spot or arc welding of the parts of the future machine.

11) Quality control and testing. The manufactured or the machined part is subjected to rigorous quality control. Robots, equipped with special sensors, which are LEDs connected to semiconductor light sensors, which are able to facilitate quality control by taking on the role of evaluators.

12) PCB Mounting. A typical board assembly process looks as follows as follows: the workpiece is placed in a special apparatus, where an adhesive composition is applied to it. After that, the workpiece with adhesive is moved to the next machine, where the components are installed (resistors). The next machine, where the components (resistors) are installed. Then the workpiece goes into the oven for quick drying of the glue, after which soldering is carried out. In this chain, each operation is performed by a specific robot, which performs strictly one action and is incapable of perform another [3].

1.3. Problem statement.

We need to design a control system for robot arm. For this robot it is necessary synthesize a control that allows it from one given point to another. Also for this robot it is necessary to synthesize the control of the robot arm, with the implementation to grasp objects.

1.4.Conclusion

In this chapter described the technological process of using robot arm, the main characteristics and components of the robots. The basic circuits were also demonstrated, including the automation scheme of the robot arm.

CHAPTER 2.
CONTROLLERS FOR DYNAMIC SYSTEMS AND THEIR DESIGN

2.1. Types of controllers used with dynamic systems

The additional element called controller is included in the structure of a system for obtaining the required performance estimates.

The following types of controllers are distinguished:

- proportional (P- controller);
- integral (I- controller);
- proportional-integral (PI-controller);
- proportional-differential (PD-controller);
- proportional-integral-derivative (PID-controller).

P- controller. The P- controller moves the regulator in proportion to the deviation of the regulated quantity from the set point e (control error):

, (2.1.1)

where is - controller transfer coefficient (P-component of the control law regulation law; its dimension is the ratio of the units of measurement of the regulating effect to the unit of the regulated quantity).

A controller obeying this law is called a static controller with one dynamic tuning parameter (gain), or a proportional P-controller.

A controller obeying this law is called a static controller with one dynamic tuning parameter (gain), or a proportional P-controller.

The static characteristic of a P- controller is the following dependence of the deviation of the regulated quantity *e* from the position of the of the regulating body in the state of equilibrium.

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Submitted by	Pashkovska Y.O.			CHAPTER 2. CONTROLLERS FOR DYNAMIC SYSTEMS AND THEIR DESIGN		Sheet	Sheets
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					CS-404		
St Inspector.	Dyvnych M.P.						
Head of Dep	Melnyk Yu.V.						

Therefore, the P- controller is called static. In this case, the static error of the regulator is found by the formula:

$$\frac{}{}, \qquad (2.1.2)$$

where is steady-state values of the controlled variable deviation

at maximum and minimum load of the object; is mean value of control error.

Transfer function, complex-frequency response and transient response of the P-controller are determined by formulas:

$$\begin{gathered} ; \\ ; \qquad (2.1.3) \\ , \end{gathered}$$

where K is a gain, such controller is called proportional one or P-controller.

Using proportional controller we can guarantee the required phase margin, but we are obliged to agree with the phase crossover frequency and the gain margin. The inverse situation is also possible: we can guarantee the required gain margin, but we are obliged to agree with the phase margin.

If we include a controller with the gain less than one in system, amplitude frequency response (the first graph of Bode plot) descends and phase frequency response (the second graph of Bode plot) be kept invariable. So, phase margin is increased. Since the frequency at which a new phase margin takes place is decreased, so the bandwidth of the system is decreased too. It results in change the rise time and overshoot: the rise time is increased and the overshot – decreased.

Proportional controllers are the simplest and allow stable control of industrial control objects. The disadvantage of such controllers is the residual unevenness of control.

I- controller. The I- controller moves the control body in proportion to the integral of the control error:

$$\frac{}{} \qquad (2.1.4)$$

where is the integration time; - total regulation time.

This controller is called astatic with one dynamic tuning parameter or integral I-controller.

Transfer function, complex-frequency response and transient response are determined by the formulas:

—;

— ‾ ; (2.1.5)

—

I-controllers can only operate steadily with objects that have significant self-alignment.

The PI controller moves the regulator in proportion to the sum of the deviation and integral of the deviation of the regulated quantity from the set point:

— (2.1.6)

where is the controller gain; - integration time.

In dynamic terms, a PI controller is similar to a system of two parallel regulators: a P-regulator with a gain of and an I-regulator with a gain of — .

Transfer function, complex-frequency response and transient response of the PI controller are determined by the formulas:

—

—; (2.1.7)

—

At infinite increase of integration time the PI-regulator turns into a P-regulator. If and tend to zero, but their ratio remains constant, we obtain the following I-regulator with a transfer coefficient —.

PI controllers are characterised by their simple design and allow to regulate a large number of industrial objects steadily and without residual non-uniformity. Therefore, they are widely used in practice.

PD-controller. The PD-control law is usually used to correction of dynamic properties of automatic control systems. An ideal proportional-differential controller has a transfer function.

(2.1.8)

where is the controller gain; is weight coefficient characterising the degree of input of the derivative into the control law, and the latter can be positive or negative.

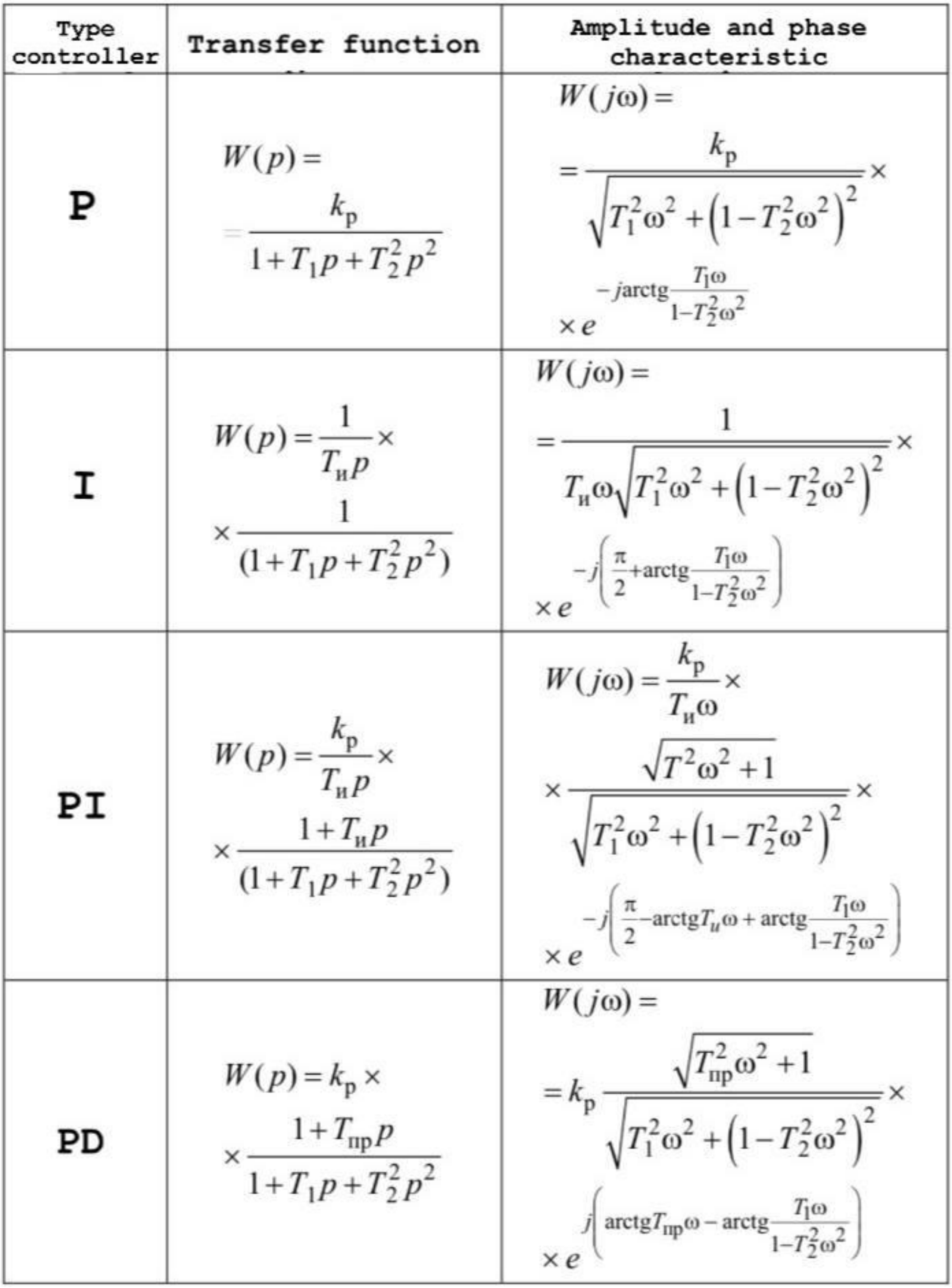
A real (inertial) proportional-differential controller has a transfer function of the form

$$\qquad \qquad (2.1.9)$$

where —.

Table 2.1.1

Dynamic characteristics of typical regulators



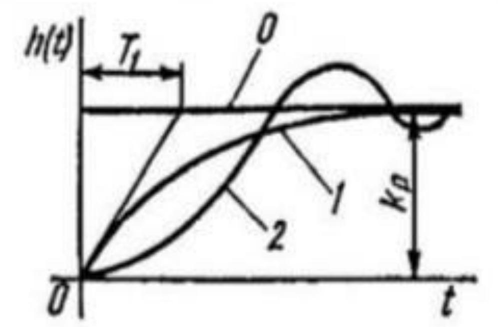
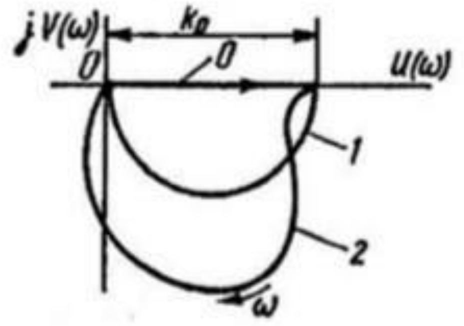
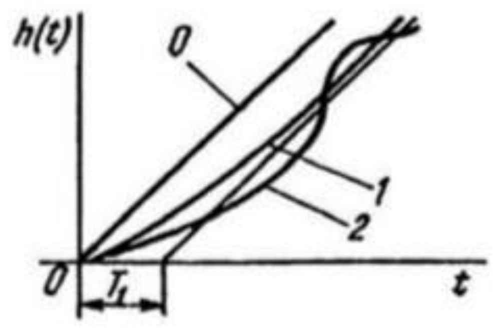
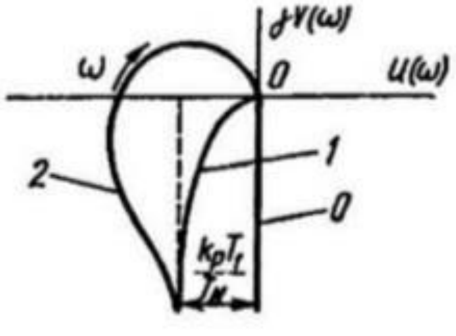
Type controller	Transfer function	Amplitude and phase characteristic
P	$W(p)=\dfrac{k_\text{р}}{1+T_1p+T_2^2p^2}$	$W(j\omega)=\dfrac{k_\text{р}}{\sqrt{T_1^2\omega^2+\left(1-T_2^2\omega^2\right)^2}}\times e^{-j\operatorname{arctg}\frac{T_1\omega}{1-T_2^2\omega^2}}$
I	$W(p)=\dfrac{1}{T_\text{и}p}\times\dfrac{1}{(1+T_1p+T_2^2p^2)}$	$W(j\omega)=\dfrac{1}{T_\text{и}\omega\sqrt{T_1^2\omega^2+\left(1-T_2^2\omega^2\right)^2}}\times e^{-j\left(\frac{\pi}{2}+\operatorname{arctg}\frac{T_1\omega}{1-T_2^2\omega^2}\right)}$
PI	$W(p)=\dfrac{k_\text{р}}{T_\text{и}p}\times\dfrac{1+T_\text{и}p}{(1+T_1p+T_2^2p^2)}$	$W(j\omega)=\dfrac{k_\text{р}}{T_\text{и}\omega}\times\dfrac{\sqrt{T^2\omega^2+1}}{\sqrt{T_1^2\omega^2+\left(1-T_2^2\omega^2\right)^2}}\times e^{-j\left(\frac{\pi}{2}-\operatorname{arctg}T_u\omega+\operatorname{arctg}\frac{T_1\omega}{1-T_2^2\omega^2}\right)}$
PD	$W(p)=k_\text{р}\times\dfrac{1+T_\text{пр}p}{1+T_1p+T_2^2p^2}$	$W(j\omega)=k_\text{р}\dfrac{\sqrt{T_\text{пр}^2\omega^2+1}}{\sqrt{T_1^2\omega^2+\left(1-T_2^2\omega^2\right)^2}}\times e^{j\left(\operatorname{arctg}T_\text{пр}\omega-\operatorname{arctg}\frac{T_1\omega}{1-T_2^2\omega^2}\right)}$

End of table 2.1.1

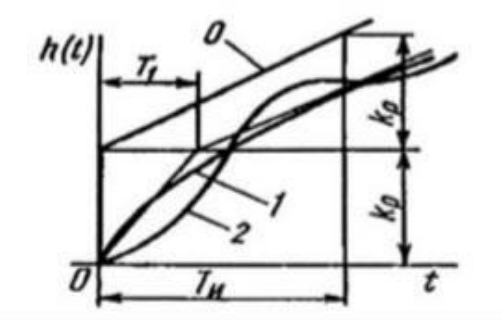
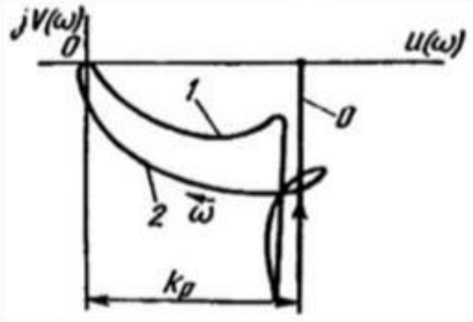
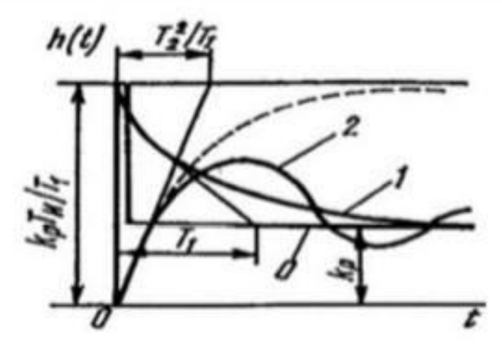
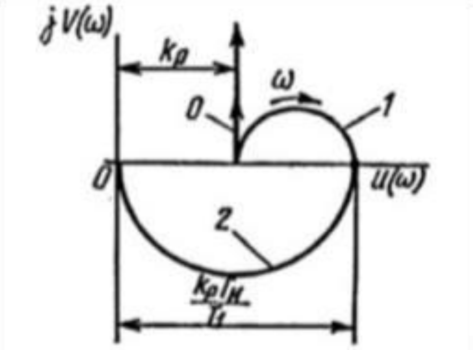
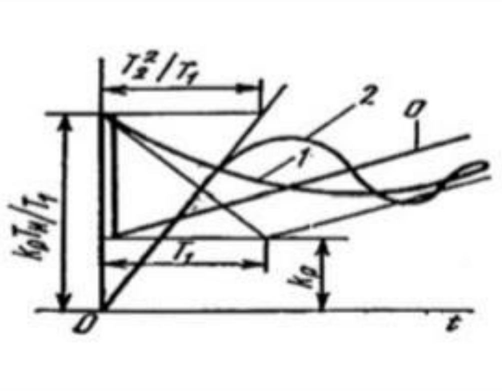
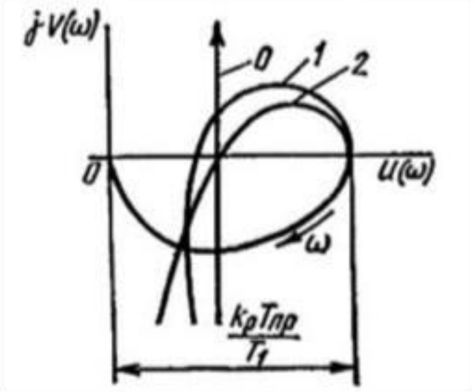
Type controller	Transfer function	Amplitude and phase characteristic
PID	$W(p)=\frac{k_р}{T_и p}\times$ $\times\frac{1+T_и p+T_и T_{пр} p^2}{1+T_1 p+T_2^2 p^2}$	$W(j\omega)=\frac{k_р}{T_и\omega}\times$ $\times\frac{\sqrt{T_1^2\omega^2+\left(1-T_u T_{np}\omega^2\right)^2}}{\sqrt{T_1^2\omega^2+\left(1-T_2^2\omega^2\right)^2}}\times$ $\times e^{-j\left(\frac{\pi}{2}-\operatorname{arctg}\frac{T_и\omega}{1-T_и T_{пр}\omega^2}+\operatorname{arctg}\frac{T_1\omega}{1-T_2^2\omega^2}\right)}$

Table 2.1.2

Transient plots of typical controllers

Type controller	Transfer function	Amplitude and phase characteristic
P		
I		

End of table 2.1.2

Type controller	Transfer function	Amplitude and phase characteristic
PI		
PD		
PID		

2.2. PID-controller structure and its influence on a dynamic system

PID controllers move the regulator in proportion to the deviation, integral and rate of change of deviation of the regulated quantity of the regulated quantity:

– — , (2.2.1)

where is the controller gain; is integration time; - anticipation time (advance, advance, differentiation), which characterises the degree of input of the derivative into the control law.

In dynamic terms, a PID controller is like a system of three parallel links: proportional, integrating and perfectly differentiating.

When , the PID controller becomes a PI controller; if, in addition, tends to infinity, it becomes a P controller. Transfer function, complex-frequency response and transient response of PID controller are determined by the formulas:

—

— ; (2.2.2)

, when $t=0;$

—, when t

PID- controllers are structurally more complicated than PI- controllers, however, in some cases they allow to improve the quality of regulation of technological parameters.

2.3. Tuning of PID-controller coefficients by the step response method

The Ziegler-Nichols method is used to adjust the PID controller coefficients by the step response. The response of the object to a step change in the control action is used.

This characteristic of the object is usually called the acceleration curve. Control objects having an aperiodic acceleration curve, as in Fig. 2.3, are represented as a series connection of aperiodic and delayed links.

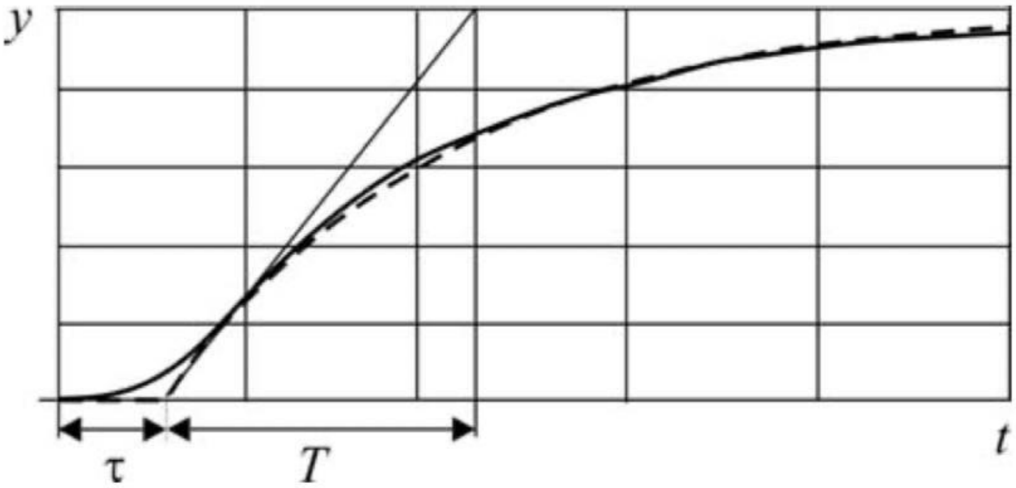


Fig.2.3. Response of the control object to a stepwise action

In this case, the transfer function of the object has the form

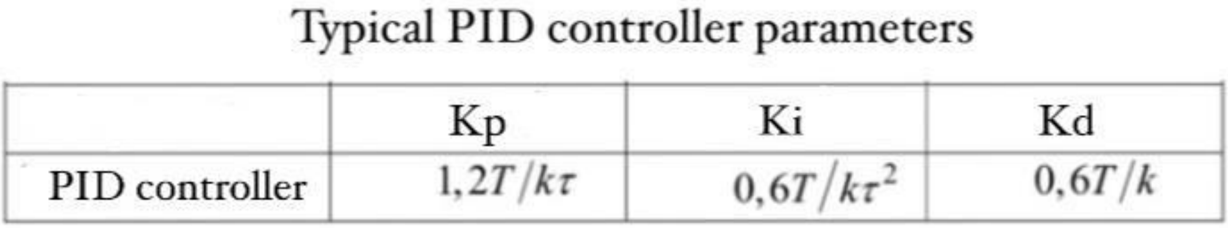
(2.3)

—— ,

where k is the transfer coefficient, T is the time constant, is the lag time.

The values of regulator parameters are calculated directly from the values of parameters k, T, . Formulas for calculating the regulator parameters are given in Table 2.3. The method gives satisfactory results if 0.15 < /T < 0.6.

Table 2.3



Typical PID controller parameters

	Kp	Ki	Kd
PID controller	$1,2T/k\tau$	$0,6T/k\tau^2$	$0,6T/k$

Regulators whose parameters are calculated using the Ziegler-Nichols method do not always provide the required quality of the control process. As a rule, additional adjustment of their parameters is required. Nevertheless, the Ziegler-Nichols method and some of its modifications are very popular and many regulator manufacturers recommend it for regulator tuning.

2.4. Tuning of PID-controller coefficients by the frequency response method

Frequency synthesis method is a method that uses the frequency characteristics of an open-loop control system based on the Nyquist criterion.

This method does not provide accurate estimates of the time characteristics, but it does provide information on the steady state behaviour of the system (low frequency region), on the stability margin and on the bandwidth of the system.

Let us obtain the equations for the synthesis of a classical PID controller. Its transfer function is represented by formula:

—— (2.4.1)

Nyquist diagram for the corrected open loop system at the cut-off frequency passes through the point , where is the phase margin (Figure 2.4).

Or else

= = , (2.4.2)

where is transfer function of the unadjusted open loop system system, is the transfer function of PID controller.

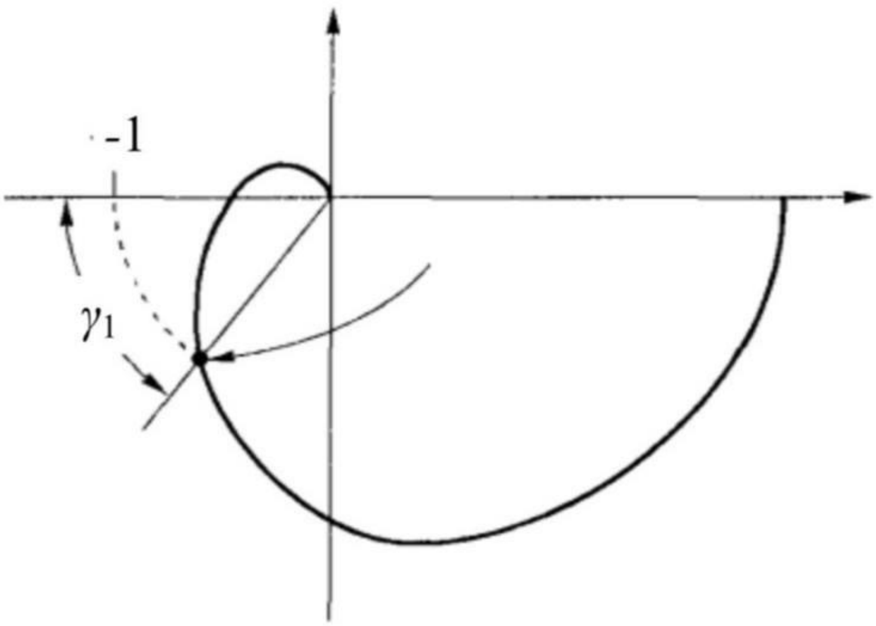


Fig.2.4. Nyquist diagram for the corrected system

Let us denote the argument of the function by and according to formula (2.4.3) we obtain:

=)—. (2.4.3)

From formulas (2.4.2) and (2.4.3) we obtain:

— , (2.4.4)

where

———. (2.4.5)

Given (2.4.5), by equating the real parts in equation (2.4.4), we obtain

———, (2.4.6)

By equating the imaginary parts:

— ———. (2.4.7)

When is known, on the basis of equation (2.4.6), the coefficient is calculated.

Then, by setting, for example, the coefficient , (based on the requirements to the quality of the system in steady state), it is possible to solve equation (2.4.7) with respect to , and vice versa.

If the cut-off frequency of the corrected system is initially is unknown, it can be selected according to relation (2.4.8) by setting the regulation time .

$$\frac{\quad}{\quad}. \qquad (2.4.8)$$

However, this relation is exact only for typical systems of the second order. For higher-order systems, it can only serve as an approximation, and a rather rough one at that.

The phase shift produced by the controller at frequency can be either positive or negative, and the modulus of the function , can be either greater or less than unity. Therefore, the only constraint on the choice of frequency is that the absolute value of angle according to the formula (2.15) must be less than 90°.

Equations (2.18) and (2.19) have a general character and are applicable to the synthesis of any modifications of the PID controller. For example, assuming that = 0, the ND-regulator will be obtained and as a result:

$$\frac{\qquad}{\qquad}. \qquad (2.4)$$

2.5. Conclusion

In this part, I analysed the types of controllers that are used with dynamic systems. I presented the structure of PID controller and how it affects on the dynamic system. Also the adjustment of PID controller coefficients by step response and frequency response method was investigated.

CHAPTER 3.
DESIGN OF CONTROL SYSTEM FOR ROBOT ARM

3.1. Design of control system with the help of Nichols diagram

The Nichols diagram is a graphical representation used in control system design to evaluate the frequency response of a system and to design controllers. It combines the gain and phase information of a system into a single plot, which can be very useful for understanding system behavior and stability margins. Here's a step-by-step guide on how to design a control system using the Nichols diagram:

1.Obtain the Open-Loop Transfer Function: start with the open-loop transfer function ( ) ( ) of the system, where ( ) is the plant and ( ) is the controller.

2.Compute the Frequency Response: compute the frequency response ( ) ( ) over a range of frequencies ω.

3.Plot the Nichols Diagram: plot the gain (in dB) against the phase (in degrees) on the Nichols chart. This plot shows how the gain and phase of the system change with frequency.

3.Determine the Desired Specifications: define the desired gain margin (GM) and phase margin (PM). The gain margin is the amount of gain increase required to make the system unstable, and the phase margin is the amount of additional phase lag required to make the system unstable.

4.Analyze the Nichols Chart: on the Nichols chart, identify the current gain margin and phase margin. The intersections of the plot with the -180° phase line indicate potential stability issues. The distance from these intersections to the -180° phase line (in dB) gives the gain margin, and the horizontal distance from these points to -180° gives the phase margin. [11]

5.Design the Controller:

- Use the Nichols diagram to design the controller ( )H(s). The goal is to shape the frequency response to meet the desired gain and phase margins.

Aerospace Control Systems Department				Explanatory Note			
Submitted	Pashkovska Y.O.			CHAPTER 3. DESIGN OF CONTROL SYSTEM FOR ROBOT ARM		Sheet	Sheets
Supervisor	Klipa A.M.					35	53
					CS-404		
St Inspector.	Dyvnych M.P.						
Head of Dep	Melnyk Yu.V.						

- Lead Compensator: If the phase margin is insufficient, a lead compensator be used to add positive phase (lead) at certain frequencies.
- Lag Compensator: If the system needs more gain at low frequencies for better steady-state performance, a lag compensator can be used.
- PID Controller: A combination of proportional, integral, and derivative actions can be used to achieve the desired response.

6.Iterate and Validate:

- Adjust the controller parameters iteratively and re-plot the Nichols diagram to check if the desired margins are met.
- Validate the designed controller by simulating the closed-loop system response to ensure it meets the performance criteria (e.g., settling time, overshoot, steady-state error).[10]

3.2. Analysis of the uncompensated robot arm model

Initial data and scheme (fig. 3.2.1) for calculating a robot hand servo control system:

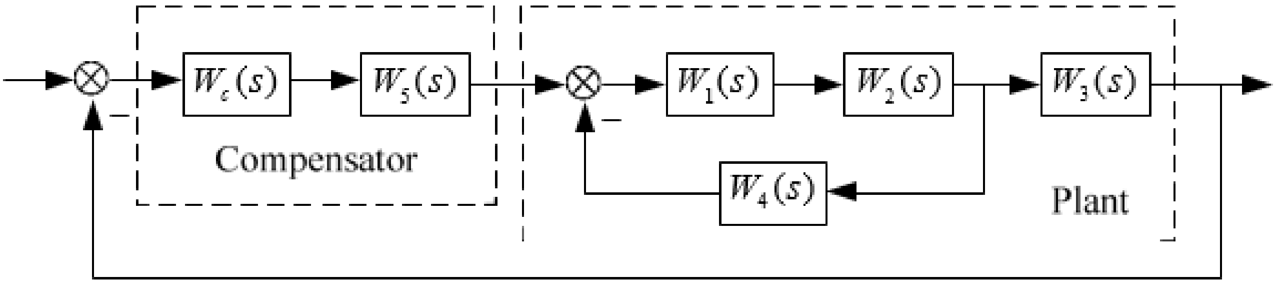


Fig. 3.2.1. Scheme of a robot hand servo control system

We used the laws of series, parallel and feedback to calculate the transfer function of the entire system.

To analyse the system for stability, we need to define some characteristics of the system.

First, let's define the zeros and poles of the system, in our case, the uncompensated system has two positive poles (in fig. 3.2.2 we see that the poles are on the right half-plane (RHP)), which indicates that the system is not stable.

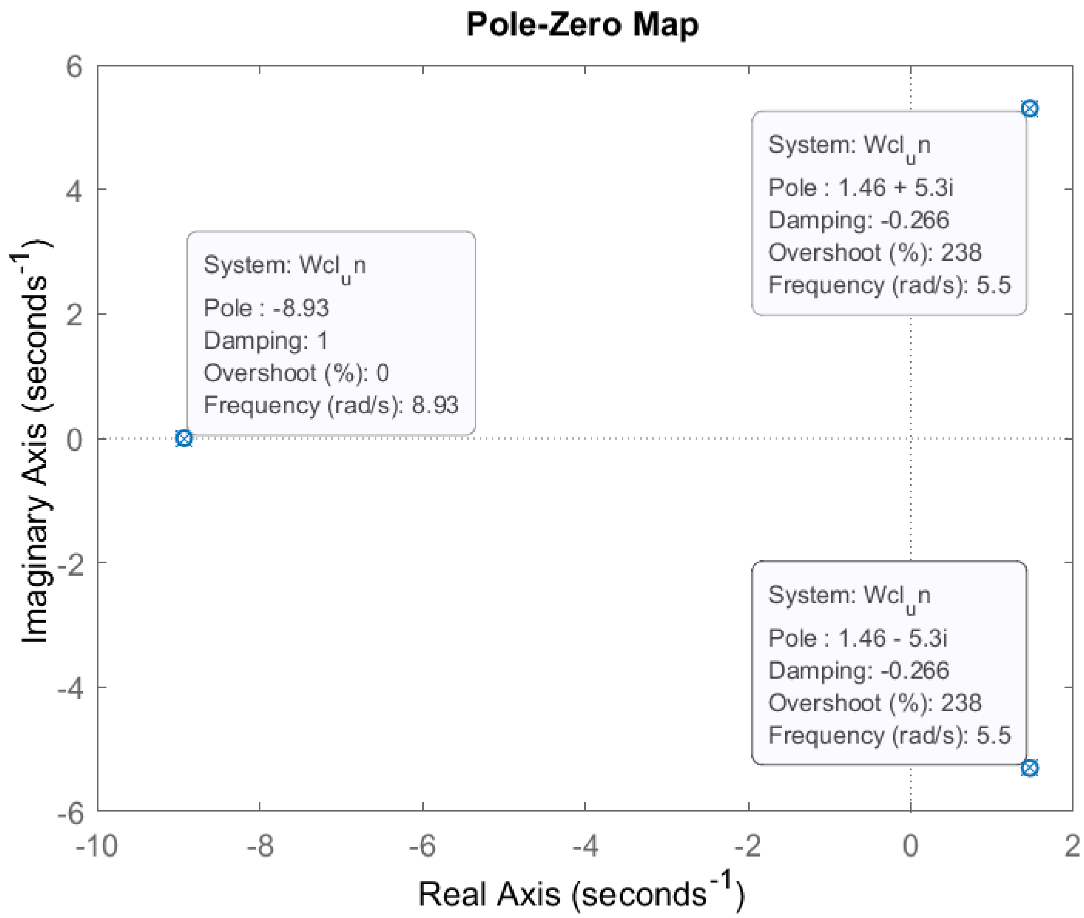


Fig. 3.2.2. Pole-zero map of the system

Zeros and poles of system are the roots of the nominator polynomial and characteristic equation.

System has not zeros.

Poles of the uncompensated closed-loop system:

From the Bode plot, you can ensure that the system is unstable. Guided by the definition of stability according to the Bode plot, if the open-loop system is stable, then the closed-loop system will be stable if the absolute value of the phase ordinate of the frequency response (the second graph of the Bode plot) at the crossover frequency is less than 180 degrees.

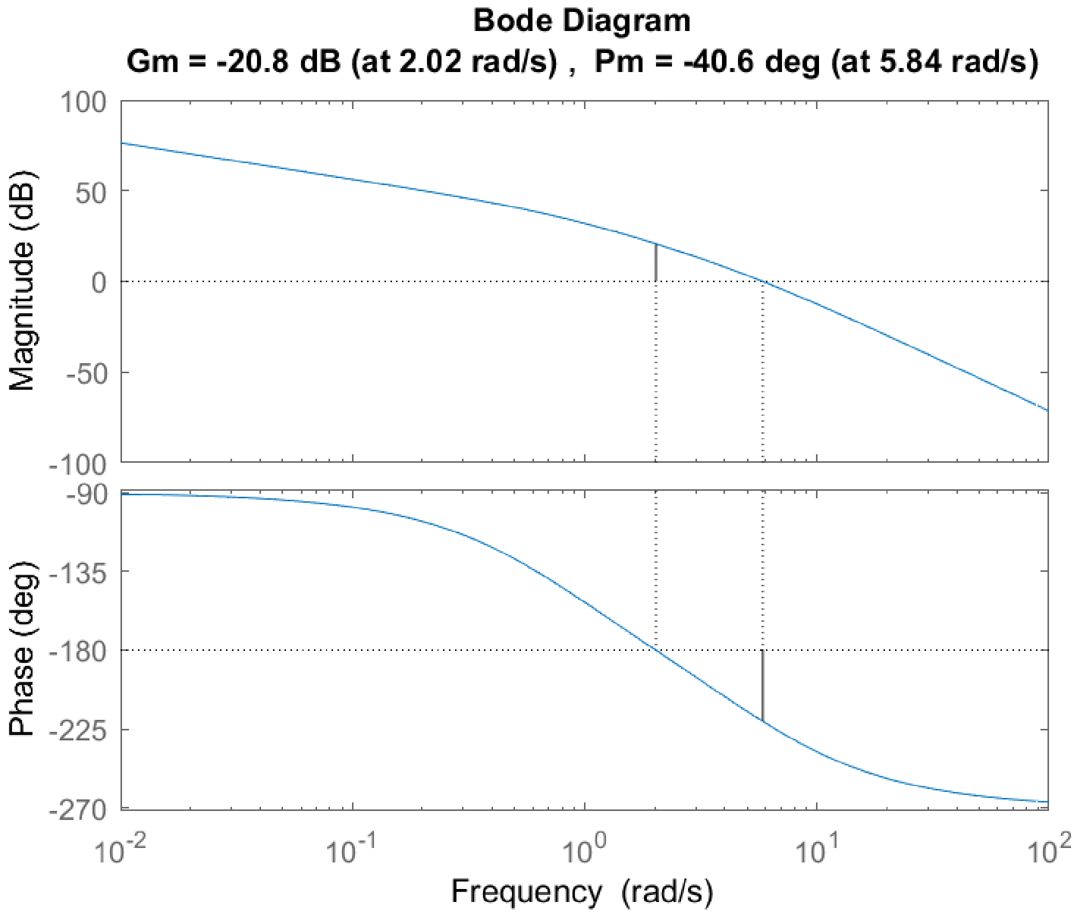


Fig. 3.2.3. Margins of uncompensated open-loop system

The graph shows that the phase crossover is smaller than the gain crossover, so the stability margin is negative. This characteristic means that the system is not stable.

The upcoming analysis will focus on creating time-based features. A step response refers to how a system reacts when the input suddenly shifts from one value to another at a specific time. On the other hand, the impulse response of a system relates to its output when the input is a brief pulse signal, characterized by its unit area and infinite height.

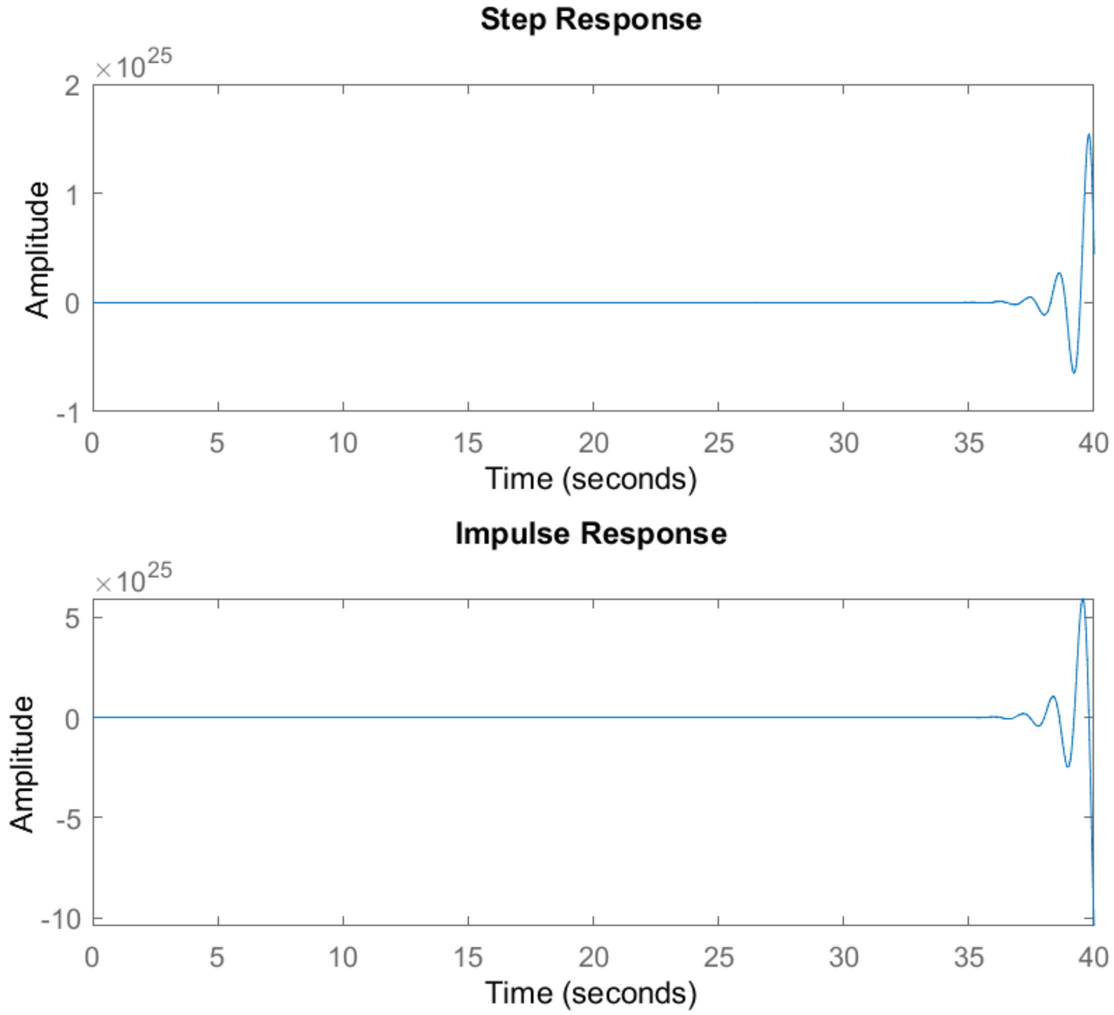


Fig. 3.2.4. Time responses of uncompensated system

Based on these characteristics, it can be concluded that the continuation of a long period on the straight line y=0, followed by two oscillations without a steady state value, indicates the instability of the system and possible negative effects that may arise in the absence of control or regulation. For a more detailed analysis, we can look at the Step response in an enlarged view (Fig. 3.2.5).

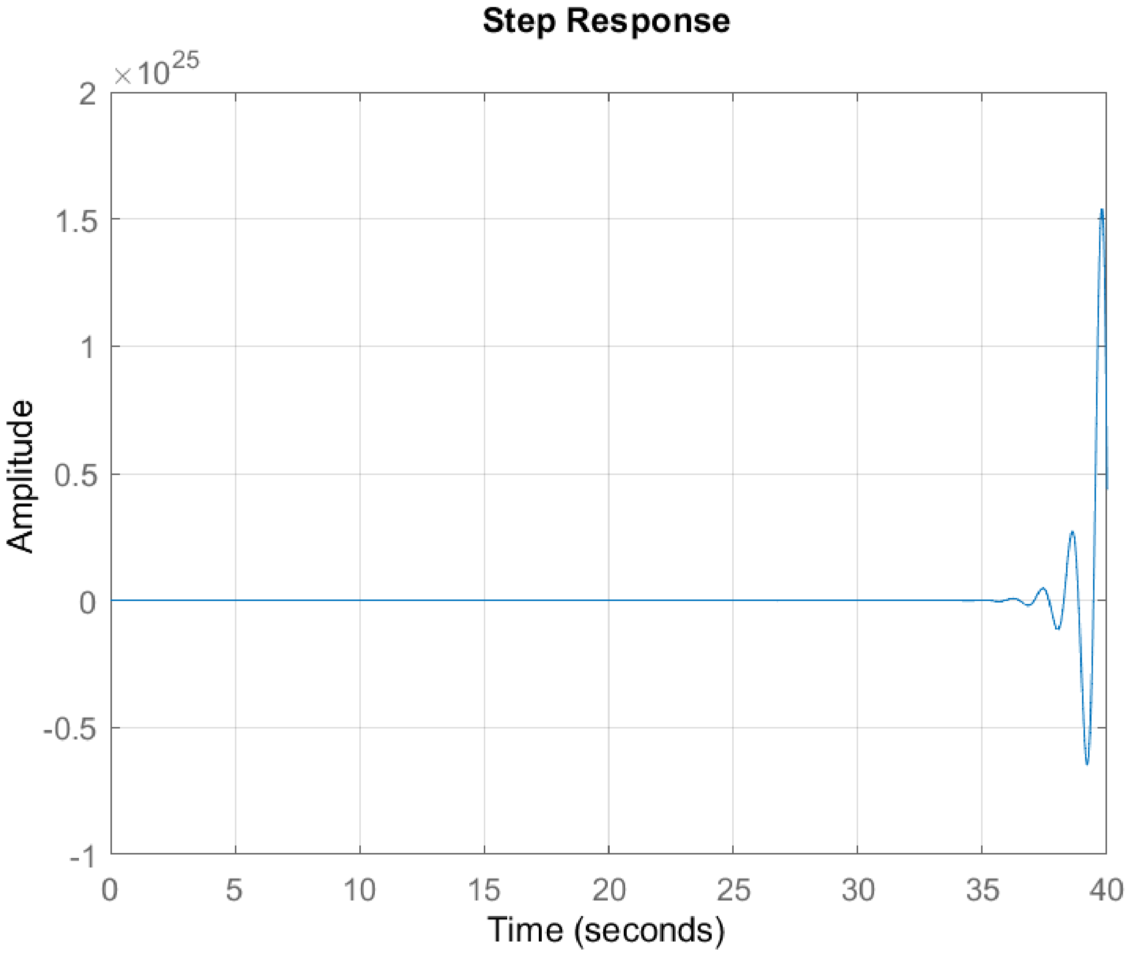


Fig. 3.2.5. Step response of uncompensated system

As can be seen from the graph, the system has no set point and no system set point time, i.e. there are no transient characteristics of this system, which means that the system is not stable.

Also, for an unstable system, we cannot determine the -norm, i.e. the system needs a controller to become stable to disturbances.

3.3. Design of PD-controller for robot arm model

We have a given frequency ω - 1.5 rad/s. We need to calculate the phase shift of the controller at this frequency.

We should to determine the gain for the proportional part of the PD-controller.

________________ ____________

Next, we determine the gain for the differential part of the PD controller.

__________________ _____________

Then we can present the transfer function of the PD controller:

_______ ____________ ________________

Let's present the Bode Diagram of this controller:

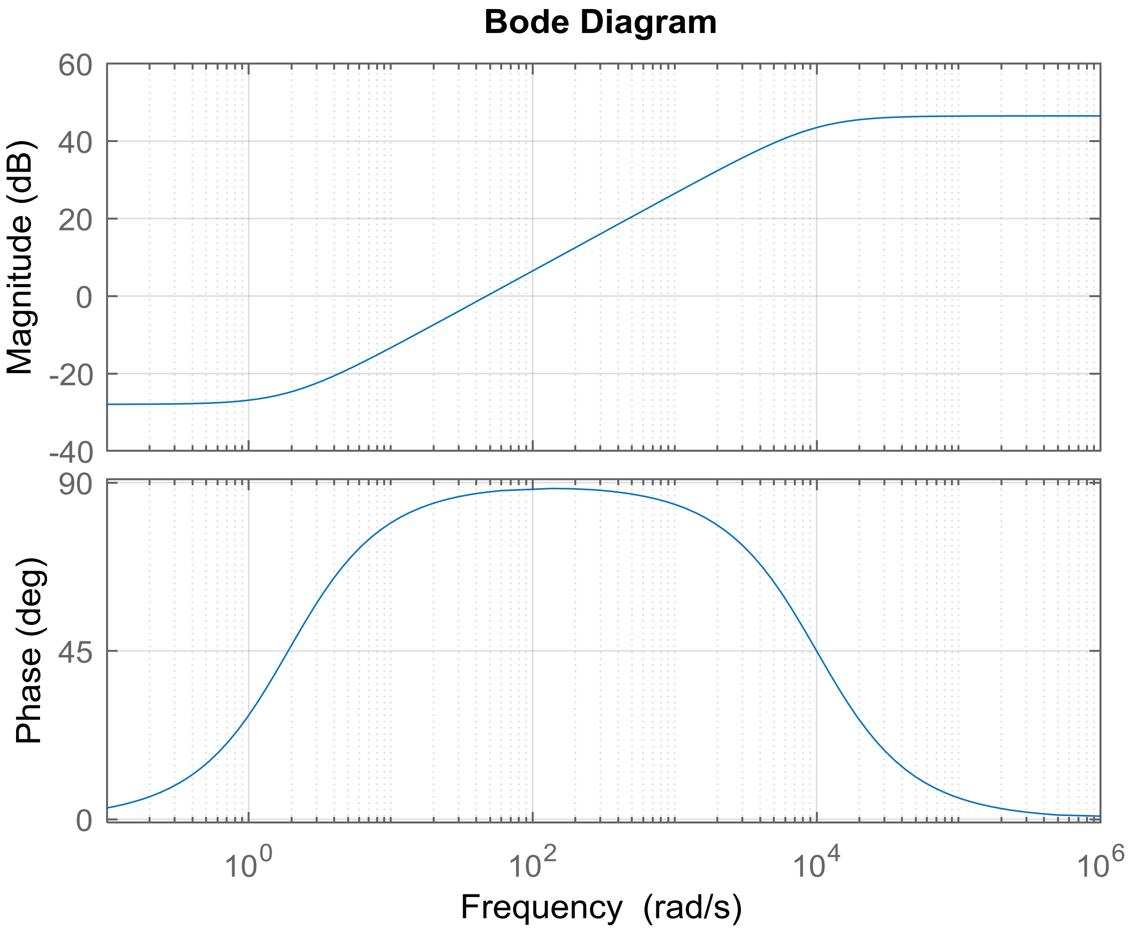
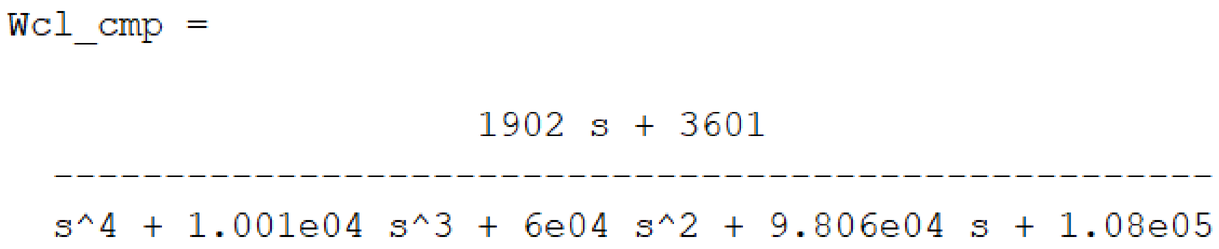


Fig. 3.3. Bode Diagram PD controller

3.4. Analysis of the compensated robot arm model

After calculating the transfer function of the PD controller, we can start analysing the already compensated system.
Calculated by Matlab transfer function of compensated closed-loop system:



```
Wcl_cmp =

                          1902 s + 3601
  ---------------------------------------------------
  s^4 + 1.001e04 s^3 + 6e04 s^2 + 9.806e04 s + 1.08e05
```

Let's start analysing the system for stability using the same algorithm. The poles of the system are negative, which indicates that the system is stable. In Fig. 3.4.1 we can see that all the poles are on the LHP.
Zeros:

Poles:

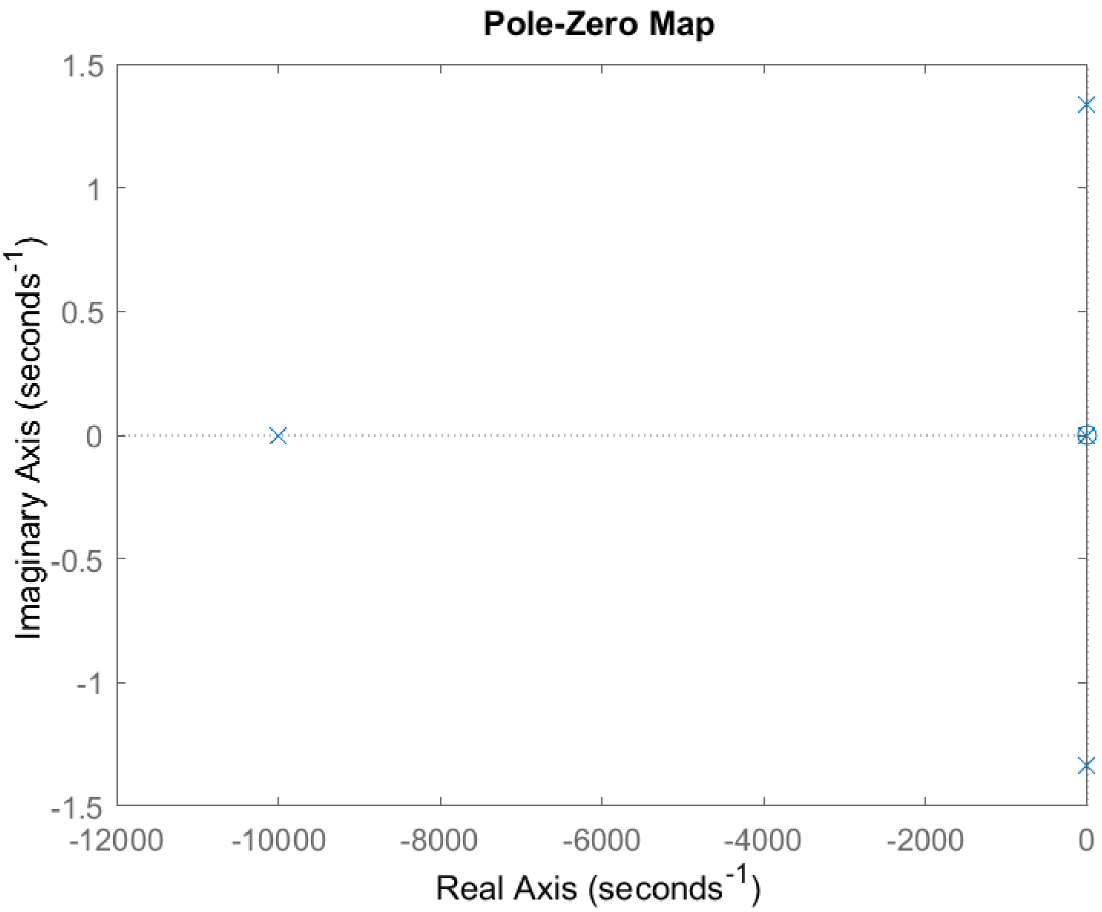


Fig. 3.4.1. Pole-zero map of the system

In order to conclude that it is possible to return the compensated system to its initial state, we construct a bode plot (Fig. 3.4.2) and simulate the system response to a single step and single impulse disturbance (Fig. 3.4.3).

From the determination of the system stability by the Bode plot, it can be seen that the open loop system is stable in terms of gain and phase margins, this means that the closed-loop system is also stable. And the system has reached the phase margin at the desired frequency, i.e. the system compensation has been successfully completed.

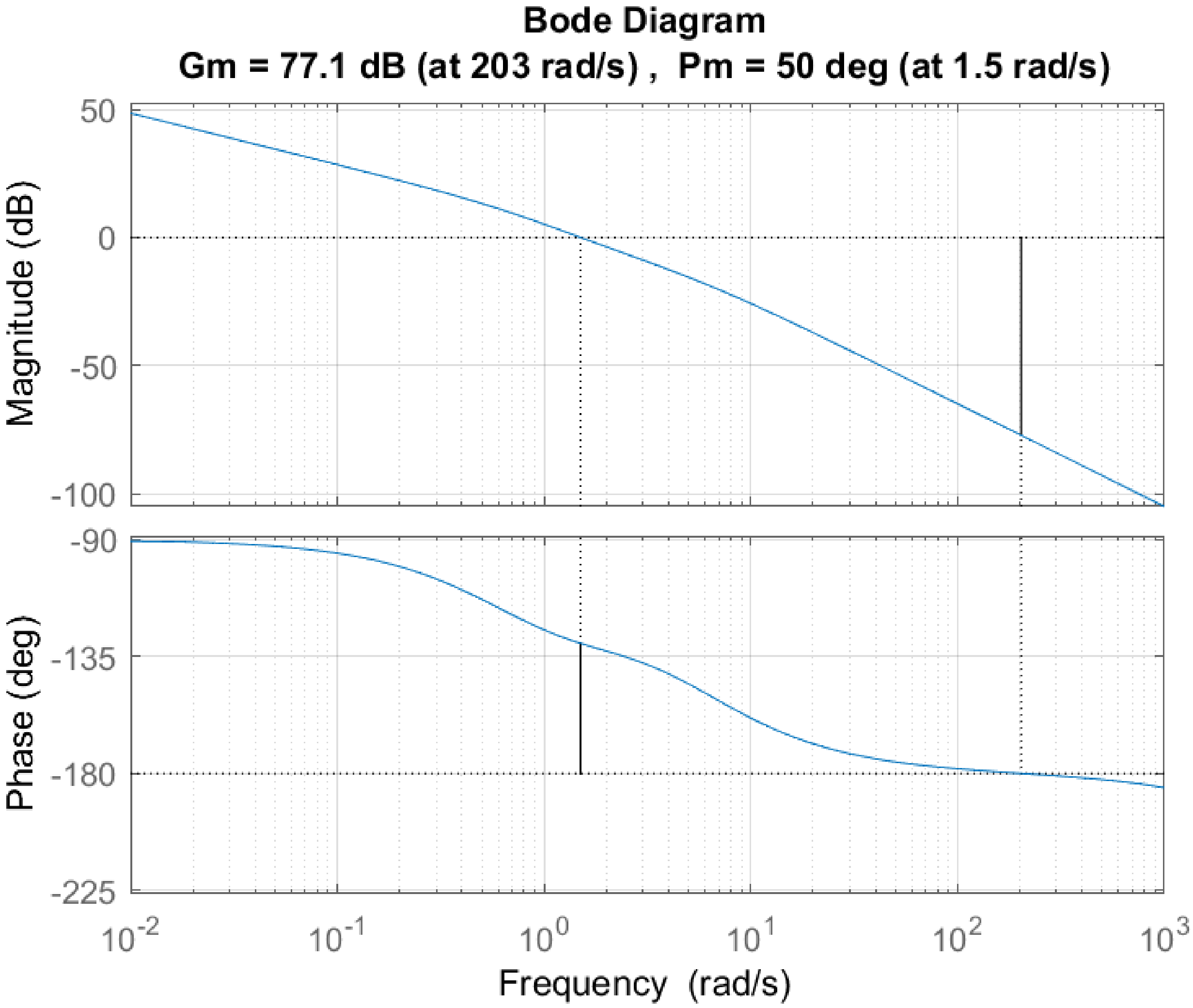


Fig. 3.4.2. Margins of compensated open-loop system

Figure 3.4.3 shows the time characteristics.

The Step response shows that the system quickly reaches a steady state without interruption.

The Impulse response shows that the system quickly smoothes out any input errors or disturbances and quickly returns to equilibrium without significant fluctuations.

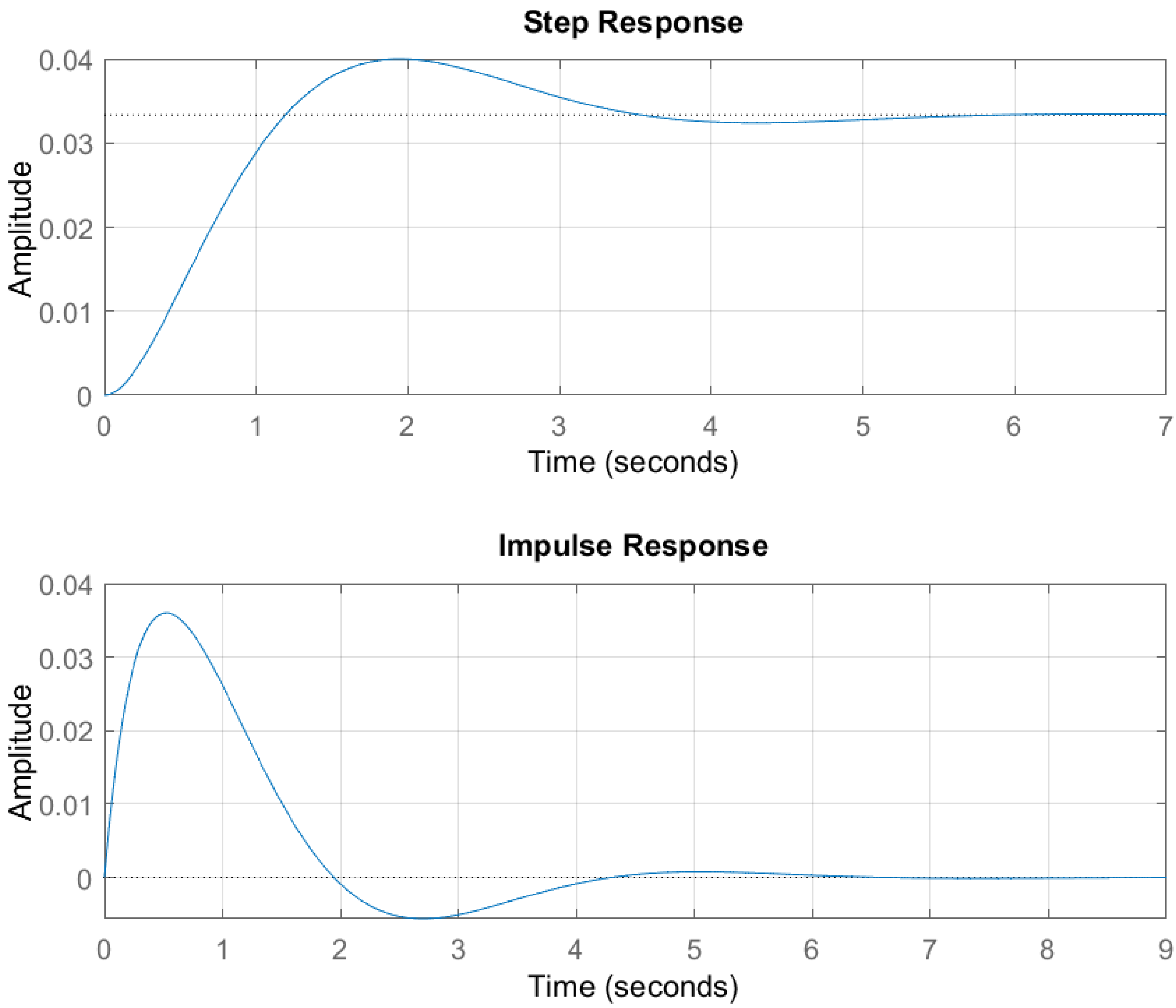


Fig. 3.4.3. Time responses of compensated system

For a more detailed analysis, we can look at the Step response in an enlarged view (Fig. 3.2.5).

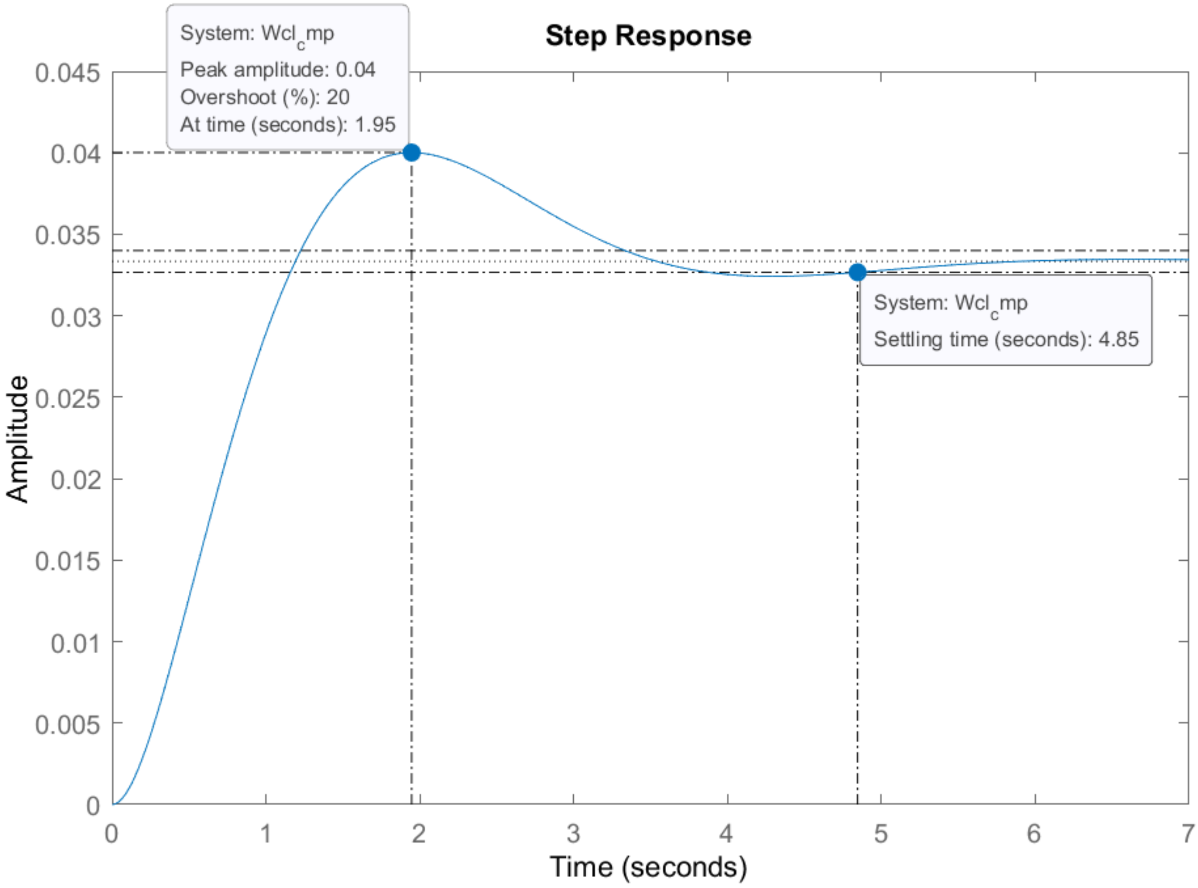


Fig. 3.2.5. Step response of uncompensated system

The step response shows the following characteristics: rise time 0.8262 s, settling time 4.8454 s, overshoot 20.0490 %, peak 0.04, peak time 1.9471 s.

-norm of compensated system is 0.0336.

3.5. Comparison of the uncompensated and compensated robot arm models

When comparing a compensated and an uncompensated system, all the characteristics we have analysed in this paper should be taken into account.

The uncompensated system has two positive poles, which makes it unstable. This is reflected in the Bode plot, where the phase shift is less than the gain, which confirms the negative stability margin.

The PD controller reduces the phase shift and increases the gain, which helps to achieve stability in the compensated system. After compensation, the poles are located in the left half-plane, indicating that the system is stable.

Analysing the time characteristics (Fig. 3.5.1), it can be seen that the compensated system reaches a steady state without oscillations and responds quickly to changes. The -norm after compensation is 0.0336, which indicates the effectiveness of the system's compensation.

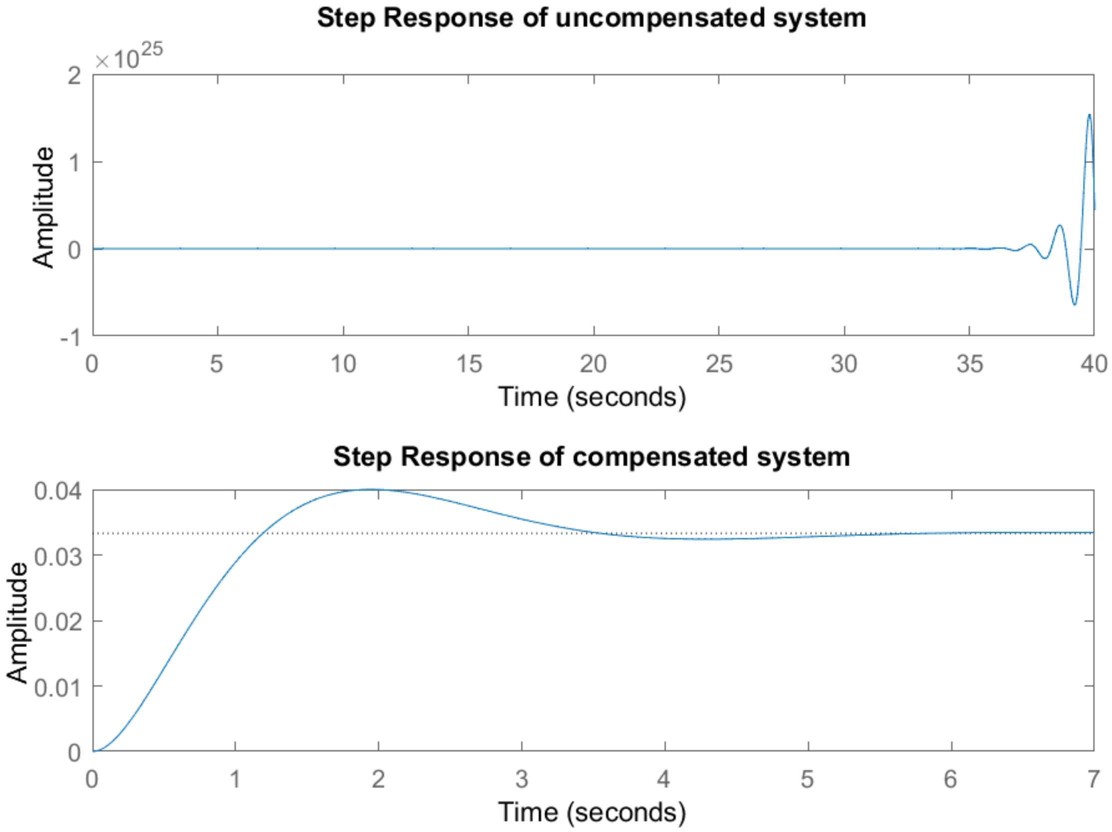


Fig. 3.5.1. Time responses of uncompensated and compensated systems

Comparing the uncompensated and compensated systems, it can be said that the compensated system has better stability performance and reaches steady state faster. This means that it is better controlled and has smaller fluctuations in response to external influences.

3.6. Conclusion

In this part, a complete analysis of the uncompensated continuous system for the robot arm was performed, the synthesis of the controller PD was carried out and then analyzing the compensated system to compare their performance and stability.

For unncompensated system was calculated transer function for the closed-loop system, stability was determined (evaluated using zeros, poles, and a Bode diagram), performance (assessed by determining settling time, overshoot, rise time, delay time, oscillation factor and number of oscillations, along with calculating the H2-norm).

For PD controller synthesis was calculated phase shift for the given crossover frequency, it was determined gain (proportional Kp and differential Kd gains), transfer function was calculated for PD controller and plotted Bode to visualize compensator impact.

For compensated system was recalculated transfer function for closed-loop system, stability was re-evaluated (determined zeros, poles and Bode diagram), performance for same metrics as the uncompensated system was reassessed and recalculated H2-norm to quantify performance.

And the last step, the results were comparison. Settling time, overshoot, rise time, delay time, oscillation factor and number of oscillations were compared. Stability of both systems was compared, showing improved stability in the compensated system. Poles and zeros showed which system had a greater degree of stability and lesser oscillation tendency. The H2-norm comparison indicated a significant improvement in overall system performance.

These results confirm that the PD compensation method is effective in achieving desired stability margins and performance enhancement in continuous control system.

CONCLUSION

In first chapter described the technological process of using robot arm, the main characteristics and components of the robots. The basic circuits were also demonstrated, including the automation scheme of the robot arm.

In second chapter I analysed the types of controllers that are used with dynamic systems. I presented the structure of PID controller and how it affects on the dynamic system. Also the adjustment of PID controller coefficients by step response and frequency response method was investigated.

In third chapter, a complete analysis of the uncompensated continuous system for the robot arm was performed, the synthesis of the controller PD was carried out and then analyzing the compensated system to compare their performance and stability.

For unncompensated system was calculated transer function for the closed-loop system, stability was determined (evaluated using zeros, poles, and a Bode diagram), performance (assessed by determining settling time, overshoot, rise time, delay time, oscillation factor and number of oscillations, along with calculating the H2-norm).

For PD controller synthesis was calculated phase shift for the given crossover frequency, it was determined gain (proportional Kp and differential Kd gains), transfer function was calculated for PD controller and plotted Bode to visualize compensator impact.

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And the last step, the results were comparison. Settling time, overshoot, rise time, delay time, oscillation factor and number of oscillations were compared. Stability of both systems was compared, showing improved stability in the compensated system. Poles and zeros showed which system had a greater degree of stability and lesser oscillation tendency. The H2-norm comparison indicated a significant improvement in overall system performance.

These results confirm that the PD compensation method is effective in achieving desired stability margins and performance enhancement in continuous control system.

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APPENDIX

```
%% Initial data
Pm = 50; tau = 0.0001; om = 1.5;
W1=tf([1],[2 11]);
W2=tf([18],[2 1]);
W3=tf([2],[1 0]);
W4=tf([0.3],[0 1]);
Wc=tf([1],[0 1]);
W5=tf([30],[0 1]);

%% Uncompensated system
% Transfer functions
W12=series(W1,W2);
W124=feedback(W12,W4);
Wc5=series(Wc,W5)
W_plant=series(W124,W3);
Wff_un=series(Wc5,W_plant)
Wol_un=series(Wff_un,1)
Wcl_un=minreal(feedback(Wff_un,1))

% Poles and zeros
[p1, z1]=pzmap(Wcl_un)
figure(1),pzmap(Wcl_un),grid on

% Margins of uncompensated system
figure(2),margin(Wol_un)

% Time responses
figure(3)
subplot(2,1,1), step(Wcl_un)
subplot(2,1,2), impulse(Wcl_un)

figure(4),step(Wcl_un)
s1_1=stepinfo(Wcl_un)

% h2-norm
%h2_un=normh2(Wcl_un)


%% Synthesize a real PD-compensator
[mag,phase]=bode(Wol_un, om)
theta=-pi+Pm/57.296-phase/57.296 %phase shift at a om freq;
kp=cos(theta)/mag %gain for the proportional part
kd=sin(theta)/(om*mag) %gain for the differential part

% Creation of transfer function of real PD-controller
gc=tf([kp*tau+kd kp],[tau 1])
%Bode plot of designed PD-controller
```

```
figure(5),bode(gc)


%% Compensated system
%Transfer functions
Wff_cmp=minreal(series(gc,W_plant))
Wol_Cmp=minreal(series(Wff_cmp,W5))
Wcl_cmp=minreal(feedback(Wff_cmp, W5))

% Poles and zeros
[p2, z2]=pzmap(Wcl_cmp)
figure(6),pzmap(Wcl_cmp)

% Margins of compemsated system
figure(7),margin(Wol_Cmp)

% Time responses
figure(8)
subplot(2,1,1),step(Wcl_cmp)
subplot(2,1,2),impulse(Wcl_cmp)

figure(9),step(Wcl_cmp)
s2_2=stepinfo(Wcl_cmp)

% h2-norm
h2_comp=normh2(Wcl_cmp)


%% Analysis of uncompensated and compensated systems
% Poles and Zeros location
[p1,z1]=pzmap(Wcl_un)
[p2,z2]=pzmap(Wcl_cmp)

% Step responses
figure(4),
subplot(2,1,1),step(Wcl_un)
subplot(2,1,2),step(Wcl_cmp)

% Main performance estimates
s1=stepinfo(Wcl_un)
s2=stepinfo(Wcl_cmp)
```