



NUMERICAL AND ANALYTICAL COMPARISON OF BOND GRAPH IN MECHATRONICS ENGINEERING EDUCATION

Thesis for the Degree of Doctor of Philosophy (PhD)

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Debrecen, 2024

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NUMERICAL AND ANALYTICAL COMPARISON OF BOND GRAPH IN MECHATRONICS ENGINEERING EDUCATION

Dissertation submitted in partial fulfillment of the requirements for the doctoral (PhD) degree in
Informatics

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Declaration of Original Authorship

This thesis is submitted to the Doctoral School of Informatics, the University of Debrecen in fulfillment of the requirements for the degree of Doctor of Philosophy. I hereby certify that the submitted work is my own work, that it was completed while registered as a candidate for the degree stated on the title page, and that I have not obtained a degree elsewhere based on the research presented in this submitted work.

Debrecen, November, 2024

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Signature

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This is the last stage of the study period, lots of the people who have been straggling in society for a long time tell me that studying is the easiest thing in the world. I could not deny it because I have not been in society to support a family. I guess I am the luckiest guy who can still be in college at his thirtyth. I cherish these years, which could be the most meaningful years of my life.

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Abstract

Mechatronics engineering is an interdisciplinary subject created by a Japanese engineer decades ago, which contains complex theories in multiple domains. Some obstacles need to be overcome during the study of mechatronics engineering, the complexity of the theory, and the conversion from the schematic to the simulation code. The dissertation proposes the Bond Graph as a unique teaching method to help mechatronics engineering students overcome these obstacles.

It is hard to understand the theoretical interdisciplinary subjects in mechatronics engineering based on the responses from the students. The Bond Graph has been proposed to apply to mechatronics engineering education, which could make difficult subjects easier for the students. The Bond Graph as a graphical language provides a modular method to divide the complex content into blocks. Mechatronics students can master the knowledge piece by piece, and then combine the modular knowledge to have the whole picture of the system.

The Bond Graph provides students with a shorter learning curve compared with the traditional mathematics method. Compared with the complex traditional mathematical methods, the Bond Graph could help students save calculating time to efficiently get the dynamic system's block diagram with a shorter learning curve during their studies.

This dissertation presents the numerical and analytical of the dynamic system in mechatronics engineering. The numerical part is the mathematical method representation of the dynamical system and examples. The analytical part is a novel graphical language representation using the Bond Graph.

The dissertation is based on the teaching experience of the "modeling and simulation" subject over four years and it has been proved that the Bond Graph is more acceptable than the traditional mathematical methods to the mechatronics engineering students based on the final test results of the mechatronics engineering students over three years.

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LIST OF ACRONYMS

IoT	Internet of Things
CPS	Cyber-Physical Systems
CNC	Computer Numerical Control
UAV	unmanned aerial vehicles
DEs	differential equations
ODE	ordinary differential equation
SISO	single input single output
PID	proportional integral differtial
DC	Direct current
SMC	Sliding mode controller
DOB	disturbance observer
UAVs	Unmanned aerial vehicles
TF	transformers
GY	Gyrators
IMBDO	inverse model based disturbance obsever
DOF	Degree of freedom
OP-AMPS	operational amplifiers

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1

Background and State of the Art

The main contribution of the dissertation is to present the Bond Graph method as a novel teaching strategy in Mechatronics engineering education. The structure of the dissertation background will follow the following logical content: Mechatronic engineering will be introduced in three categories, including the sum of Mechatronics engineering, applications of mechatronics engineering, and the control theory in Mechatronics engineering. The control theory plays a critical role in Mechatronics Engineering since Mechatronics research comes with the control theory in certain applications.

The case study covers various topics, from fundamental to advanced. It begins with a demonstration using a DC motor, making it suitable for undergraduate students to learn about linear and nonlinear control methods. Disturbance Observer has been developed over the decades, with the novel Bond Graph representation of disturbance observer making it a practical level.

In the following chapter, the Bond Graph as the main strategy is presented in great detail. Its synergistic characteristics and powerful programming ability enable it to handle complex modeling problems effectively.

Education in Mechatronics is discussed in the next chapter. The intricate nature of Mechatronics presents challenges in education. Compared with the traditional method, the Bond Graph method provides a powerful and graphical language tool to accelerate the learning process in mechatronics subjects. In the meantime, the Bond Graph can support modeling and simulation not only from a force perspective but also from the standpoint

of Lagrangian energy.

1.1 Mechatronics Engineering

Mechatronics is a combined word created by a Japanese engineer in the 60s 20th century [1]. It is a combination of the front part of the mechanical and the back part of the electronics. Mechatronics is widely recognized as an interdisciplinary field that encompasses various domains, including mechanical engineering, electronics, and control theory.

Mechatronics has become an essential subject in multi-domain engineering because of its interdisciplinary characteristics, which include the electrical, mechanical, and hydraulic domains these three categories [2].

Mechatronics is not merely a combination of mechanical and electronic systems, but rather a system focused on integrated control. [3]. These definitions and introductions of mechatronics are well-stated and accurate, but not detailed enough to describe the whole capture of mechatronics.

The theoretical part of mechatronics is a youthful subject [4] with the understanding from engineers given from the mechatronics characteristics and philosophy. For the practical part of mechatronics, it is applied as an integration of computer science, control theory, electrical engineering, and mechanical engineering. In the dissertation, the Bond Graph methodology is provided as a solution to merge these fields into mechatronics engineering. The details of the Bond Graph are introduced in subsection 1.2.

1.1.1 Development of the Mechatronics

Mechanical engineering became a popular subject until scientists came up with the concept of automation. After several years, the first computer was invented by the Americans. Automation presents its beauty in the industry and mechanical engineering as well. In the early period, it is some industrial mechanical applications and devices with sensors and feedback integration [5]. Early developments included the integration of sensors and feedback control systems into mechanical devices, leading to the automation of

manufacturing processes. There are three stages of the development of mechatronics.

This first stage pushes the process of the development of automation mechatronics. It started with the initial stage of a simple combination of machinery and electronics. During this period, people only had the preliminary idea of combining electronic technology with mechanical industrial production. The specific integration has not been able to achieve technological breakthroughs, and they are more stuck on a theoretical level. After several years of development, it reaches a second level. The second stage is the prosperous development stage. In this stage, with the development of society, many theories can move towards reality [6]. The development of electronic technology has made new progress, but it is not yet fully integrated with our machinery. People have initially applied theory to practice but still cannot reach the level we expected [7]. The third stage focuses on the direction of intelligence development, marked by rapid technological advancement.

As shown in Figure 1.1, mechatronics engineering involves complex concepts with high nonlinearity. This makes the subject challenging to understand.

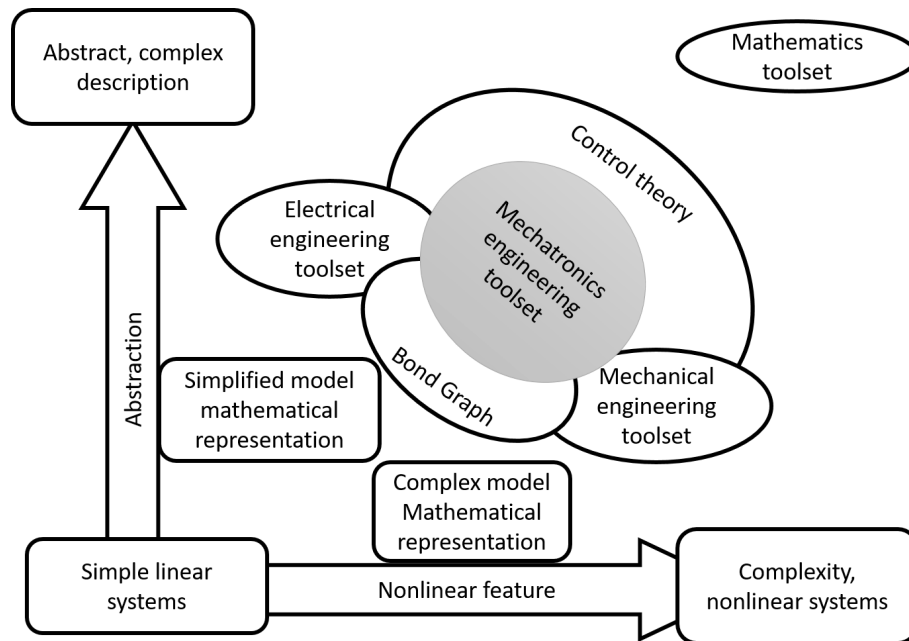


Figure 1.1. *The definition of the Mechatronics [8]*

As we all know, mechatronics has gradually entered all kinds of fields and provided different technical services for specific purposes. However, with the continuous progress of society, there is also constant development towards diversification and refinement in many

fields of daily life. Especially in recent years, some special industries have emerged and developed, and they have higher requirements for mechatronics [9]. It requires mechatronics to conduct targeted research on these emerging industries to ensure the requirements of emerging industries for mechatronics [10]. In view of the limitations of the industry, researchers should break the tradition and conduct innovative research on mechatronics to ensure that mechatronics can adapt to the requirements of various industries and truly realize the management of mechatronics engineering integration.

Mechatronics engineering has the following potential trends in the following fields:

1. Neural networks are an efficient method to process plenty of data using the way of human thinking. The robustness is a crucial characteristic in mechatronics, and the neural network plays an efficient role in the analysis of the parameters [11].
2. Modularization is the main direction of mechatronics in the future [12]. Mechatronics will develop in the direction of modularization, which could provide production faster and cheaper. This can meet the new consumption requirements of customers. At the University of Debrecen, the mechatronics engineering subject was taught in the module, which is better for the students to digest the complex knowledge. Information technology makes modular production more widely used.
3. Internet of Things(IOT) After entering the new era, the development speed of network technology is amazing. The development and application of the Internet of Things have an important impact on mechatronics. There are many types of products involved in mechatronics, and their network-oriented directions are also different [13]. With the popularization of network and IoT remote technology, the development of network control technology and the application of the network in the electromechanical industry will become more and more extensive. The development of local area networks and Fieldbus technology has made electrical appliance networking a development trend.

All in all, with the improvement of people's living standards and the continuous innovation of science and technology, the development of mechatronics is no longer a single development. It will be integrated into all walks of life and used together with various advanced technologies [14]. In view of the good development prospects of mechatronics,

researchers should pay attention to the shortcomings in the current development process of mechatronics and actively take corresponding measures.

1.1.2 Applications in Mechatronics Engineering System

Mechatronics is a technology based on the mechanical and electrical theory to carry out advanced technology to improve work efficiency. In the meantime, the combination of Mechatronics technology and the construction machinery industry provides an efficient solution for mechanical operation from the industrial point of view. Compared with the Mechatronics system, the Cyber-Physical System (CPS) is combined with the hardware and software [15].

1.1.2.1 Cyber-physical System in Mechatronics Engineering

The first layer of the Cyber-Physical System contains the traditional mechanism control with the known adjusted parameters [16]. CNC machine speed control belongs to the first layer. By applying mechatronics technology in the module design process of large-capacity memory, mechatronics technology can enrich CNC functions on the original basis and achieve the multi-process and multi-channel control objectives of CNC machine tools [17].

The second generation of the CPS is focused on the alternative of the control modes and the optimal control during the adjustment [16]. The mechanisms of control rely on the sensing data from the environment in each operation mode. By applying mechatronics technology to the cyber-physical system, dispersed systems can be combined in a simple way to achieve the comprehensive goal of dynamic optimization of the system [18].

Self-learning during the control process is the third level of the Cyber-Physical System in Mechatronics [16]. The construction and implementation of industrial intelligent robots based on intelligent self-learning technology and Cyber-Physical Systems in mechatronics technology can enable the entire function to be realized [19]. From the perspective of the implementation principle of industrial intelligent robots, it covers information technology, sensing technology, control technology, etc. With the support of fuzzy control theory and neural network algorithms, the entire control system has artificial intelligence thinking

[20].

The fourth layer of the CPS in Mechatronics engineering is for future trends. It will be set up as the fundamentalism of Industry 4.0 [16]. There is no certain limitation for the system structure, the human will be considered as the supervisor for the CPS in the Mechatronics system.

The CPS presents the principles and the potential trends in Mechatronics Engineering. In the meantime, the Bond Graph technology could be implemented into the first two layers of the CPS by providing the modeling and simulation technology in Mechatronics engineering.

1.1.2.2 Extended Applications in Mechatronics Engineering

Mechatronics engineering is involved in many other advanced fields such as biomedical engineering and aerospace engineering. Mechatronics engineering provides basic sensors with mechanical control fundamental structures for surgical robots and prosthetics [21]. The design and control process of unmanned aerial vehicles (UAV) is closely linked with smart educational mechatronics systems which are designed to meet the needs of companies [22].

All these interdisciplinary subjects can merge into Mechatronics engineering, and the Bond Graph method provides a unity solution for the analysis and control method.

1.1.3 Control Theory in Mechatronics Engineering

Control theory is an interdisciplinary branch of mechatronics engineering and mathematics that deals with the dynamical system behavior. The input of the dynamic system is called 'reference value' and the variables in the system should respond to the reference value. The control process operates the input values of the system to reach the desired output of the system. The purpose of the control theory is to have a steady dynamic system output with the help of controllers, which means the system could maintain the output around the desired value.

The differential equations(DEs) could represent the continuous dynamic system, which requires certain knowledge of mathematics. If the differential equation is a linear dynamic

system with constant coefficients, the transfer function can be derived from the relationship between the input and output by Laplace transformation. In this case, the ordinary differential equations(ODEs) are a useful tool in mechatronics control theory. Another essential content of the control theory is the block diagram, which is normally a typical graphical language to demonstrate the dynamic control system in mechatronics.

1.1.3.1 Modern Control

The development of modern control theory was driven by the rapid emergence of space technology in the mid-1950s [23]. The development of space technology urgently requires the establishment of new control principles to solve control problems such as launching space rockets and satellites accurately into predetermined orbits with the least amount of fuel or the shortest time [24]. Such control problems are so complex that they are difficult to solve using classical control theory.

The Soviet scientist Potryagin proposed a new approach to integrated modern control system called maximum principle [25]. From 1960 to 1961, American scientists R.E. Kalman and R.S. Bush invented the Kalman-Bush filter theory, thus making it possible to effectively consider the influence of random noise present in control theory, expanding the scope of research in control theory to include more complex control problems [26]. Almost at the same period, Bellman, Kalman, and others systematically introduced the state-space model method into control theory. It is well known that the state-space model method plays a key role in revealing and understanding many important properties of modern control systems [27].

The object of study of classical control theory is single-input single-output automatic control systems, especially linear constant systems. Classical control theory is characterized by the input and output characteristics as the mathematical model of the system [28]. Modern control theory includes a wide range of disciplines, the main aspects are: open loop control, close loop control, linear system theory, nonlinear system theory, and adaptive robust control theory [29].

Modern control can not be avoided if the case study is related to Mechatronics engineering. In the dissertation, the general introduction of the control theory is briefly presented in the following subsection. The close loop control is the main frame of the

modeling and simulation target, and the linear and nonlinear control are the basic controls applied in Mechatronics engineering education. In the meantime, adaptive robust control is illustrated in the subchapter 1.1.3.5 because it is another popular teaching material. The DC electrical machines are primary models in modeling and simulation subjects. They share similar characteristics to Bond Graph, which utilizes a simple solid background to solve complex problems. The disturbance observer is another case study in Mechatronics engineering education materials. The basic frame Bond Graph representation is described in section 3.1.1.

1.1.3.2 Open Loop and closed Control

An open-loop control system has no feedback loop where the output is controlled only by the system inputs. There is only sequential action between the controller and the controlled target without a feedback connection under a signal control direction. The open loop can maintain a certain accuracy if the system characteristics and values are relatively stable with a small external disturbance.

A closed-loop control system contains a feedback control between the input signal and the feedback [30]. The closed loop is a measured value of the output of the system compared with the desired value, resulting in a deviation signal, which regulates the control signal to adjust the output value as close as possible to the desired value [31]. Compared with open loop control, the closed loop is practical in the Mechatronics education case study. It is common for Mechatronics students to meet linear and nonlinear closed-loop control case studies during the modeling and simulation study activities. The flowing subsection distinguishes the linear and nonlinear control in the modeling process.

1.1.3.3 Linear Control

Linear control theory is a simple and relatively mature branch of modern control theory. It focuses on the observation and control of the states in the linear control system with the basic analysis state-space methodology.

The Proportional–Integral–Derivative (PID) controller is widely used as a typical controller in the linear control system. [32]. In industrial process control, PID control has

the advantages of a simple principle, strong robustness, and a wide range of practicality. It is regarded as a mature technology and the most widely used control system [33]. Since the late 1930s, PID control has become the most mature and widely used control method in dynamic control systems [34], which are familiar to technicians and operators. In industrial process control, it is difficult to establish a precise mathematical model of the controlled object, because of the changing parameters of the system, so the price of control theory analysis and synthesis of the cost is relatively higher [35]. Therefore it is a set of control methods summarized in long-term engineering practice. The PID controller is a continuous design method process, which requires a relatively short sampling periodization to achieve the desired value. It is well presented that the PID controller could reach a more satisfactory result during the long-term practical operation experience and theoretical analysis [36]. In this case, PID control is commonly used in mechatronics education due to its well-established characteristics.

In the dissertation, the PID controller is implemented using Bond Graph representation in the subsection 2.3.3. The control theory reaches the synergy purposes with the help of the Bond Graph graphical language.

1.1.3.4 Nonlinear Control

The linear controller is inapplicable to more complex control devices and more kinds of objects to be controlled with the upgraded technology. At the same time, nonlinear control is also practical with a variety of higher requirements in the control theory. However, the theory of nonlinear systems area is still mainly limited to the motion stability of the system [37], the control and observation problems of bilinear systems, and nonlinear feedback problems. A nonlinear control system is one in which the state and output variables of the system are affected by external conditions that cannot be described by a linear relationship [38]. Since the mid-1970s, certain methods derived from differential geometry theory have provided powerful theoretical tools for analyzing certain types of nonlinear systems [39]. Since the components that make up a system are nonlinear in nature to varying degrees, absolutely linear systems do not exist in real life. Therefore, it is necessary for Mechatronics undergraduate students to learn about the nonlinear control system.

One of the most typical nonlinear controllers is the sliding mode controller (SMC). The sliding mode controller is a typical controller that is easy to apply from a mechatronics point of view but sophisticated to analyze in terms of mathematical theory.

Sliding mode control, as a branch of variable structure control, was proposed by Soviet scholars in the 1950s [40]. An important advantage of sliding mode control is robustness with excellent insensitivity to model errors of the controlled object, variations of object parameters, and external disturbances when the system is in sliding mode. It has been widely used in the field of robot control, due to the simplicity of the algorithm of the variable structure control system, the fast response speed, and the robustness to external noise disturbances and parameter uptake [41].

The main challenge in applying sliding mode control practically is that when the state trajectory reaches the sliding mode surface, it's difficult to strictly slide along the surface to the equilibrium point. Instead, it tends to move back and forth across the sliding mode surface, resulting in chattering. [42]. Chattering avoidance became another critical topic since the sliding mode controller was invented decades ago [43]. However this chattering cannot be eliminated, which is a pain point of sliding mode control, most of the mainstream methods are currently using filtering, fuzzy control, neural networks, and other methods to mitigate the tremor [44, 45]. In this dissertation, an adaptive robust sliding mode controller is applied to get a better performance in tracking trajectory in the subsection 2.3.5.

The sliding mode controller has been used in many fields because of its robustness and easy realization characteristics [46]. There are three main reasons for the wide application of sliding mode control: a) good control performance for nonlinear systems, b) the applicability to multi-input and multi-output systems, and c) the establishment of good design criteria for discrete-time systems [47]. In this case, the sliding mode controller becomes a perfect education material for the nonlinear controller teaching in mechatronics engineering [48]. The sliding mode controller aims at dynamic system control with robustness against uncertainty. In reality, there is no perfect controller because the theoretical concept focuses on ideal situations. PID controllers have a quick response but result in a relatively unsteady dynamic system. In comparison to the PID controller, the sliding mode controller is more robust in the presence of uncertainty [49].

Modeling and simulation play a crucial role in mechatronics engineering. Mechatronics is a complex, interdisciplinary subject, which can be challenging for students to grasp. Therefore, it's important to introduce effective methods and tools to help students better understand the concepts. While many researchers focus on the application and performance of the sliding mode controller, this dissertation proposes a novel representation for modeling and simulating both the PID controller and the sliding mode controller. The Bond Graph is recognized as an innovative tool that can assist professors in teaching modeling and simulation in educational settings.

The Sliding Mode controller Bond Graph representation is shown in subsection 2.3.5.

1.1.3.5 Adaptive Robust control System

The control system is designed to mimic biological adaptive capacity to automatically adjust its characteristics. Adaptive control can be seen as a type of feedback control system that can intelligently adjust its characteristics based on environmental changes. This enables the system to operate in an optimal state according to specific standards. [50]. Adaptive control was originally used in aerospace applications, with the development of computer technology, adaptive control has also been successfully applied in the field of the chemical industry, and mechatronics engineering [51]. The advantages of adaptive control can be concluded in the following: 1) The controller can be adjusted; 2) An additional adaptive loop; 3) The applicable object accepts a wide range of perturbations [52].

The adaptive control has strong enough robustness to enhance the response of the speed control of the DC electric machine. Based on the findings, an adaptive robust sliding mode is modeled to upgrade the sliding mode to get better performance on oscillation and amplification compared with a simple sliding mode controller with a general target simulation. The adaptive control as educational materials aids students in gaining a better understanding of robust nonlinear control, including adaptive robust sliding mode control. In the meantime, the Bond Graph provides a novel demonstration of the control method from the graphical point of view.

1.1.3.6 DC electrical machine

DC electrical machines are a common industrial device because of their high efficiency and speed control ability. From the theoretical point of view, there are two fields in the DC motor, the mechanical part and the electrical part [53]. It is well-designed to express the synergy in the mechatronics engineering subject. DC motors are also widely used in educational content due to their intuitive simulation and controllability [54]. In brief, DC electrical machines are frequently used as actuators in industrial applications, in the meantime they are also well-suited for educational purposes due to their easy modeling characteristics. DC electrical motors and DC generators can be interchangeable, making DC electrical machines suitable teaching materials for Bond Graph modeling in Mechatronics Engineering. The relationship and the theory of interchangeable process are briefly described using Bond Graph in subsection 2.2.1.

1.1.3.7 Disturbance Observer

A good case study can provide students with a better grasp of learning Mechatronics engineering subjects. Disturbance removal is a critical step in the control of a dynamic system in Mechatronics Engineering. In this case, the disturbance observer is considered educational material for the Bond Graph representation.

The disturbance observer(DOB) adjusts the control input to observe external disturbances and changes in model parameters [55]. The sources of the disturbances may include variations in external load parameters and the effects of friction due to operating conditions. Compensation for the equivalent is introduced in the control process to achieve complete control of the disturbance. [56].

DOB is applied in many fields to benefit human life, such as the remote control of unmanned aerial vehicles(UAVs) [57] and the wheelchair to help the rehabilitation of the patient [58]. DOB donates a robust solution to obtain high performance in the presence of external disturbances and system uncertainties. In this case, the disturbance observer is considered a practical tool in nonlinear dynamic systems [59].

In the meantime, the direct and inverse disturbance observer is the essential method of improving the performance of the disturbance observer in the dynamical control system

[60]. Both of the methods could subtract the accurate estimation of the disturbance from the measured output to obtain a better output estimate. The direct model disturbance observer presents the dynamic system directly rather than computing the inverse model. The disturbance observer is a robust control method with some limitations in dynamic control [61]. In the dissertation, a direct and inverse disturbance observer Bond Graph representation is proposed in subsection 3.2.

1.2 Bond Graph

The Bond Graph is a graphical language to illustrate the process between the modeling and the simulation. Bond Graph gives a concise description of a complex system in the form of a vector, which greatly improves people's insight into the behavior of engineering systems. The power bond graph (Bond Graph for short) was proposed by H.M. Paynter of MIT in 1959, and after several years of development and refinement, it has been gradually developed and promoted to become a very effective dynamic modeling and analysis method that can uniformly deal with a wide range of engineering systems in the energy domain [62]. At present, the Bond Graph method has been widely used in dynamic analysis and control research across various engineering fields such as mechatronics, mechanical, thermodynamic, fluid, electronic, and magnetic systems [63]. Especially in recent years, its applications have been extended to agricultural, solar, and nuclear energy systems. During the operation of the system, some components produce energy, some consume energy, some enable energy to be transformed from one form to another, and some only transfer energy [64]. These components are grouped into categories according to their function, and by combining them organically they can be described as physical systems.

The core idea of the Bond Graph method is that the energy of an engineering system is conserved, and the dynamic process is to adjust its power flow under specific incentives [65]. It is well defined by a unified method of describing the composition, conversion, inter-logical relationships, and physical characteristics of the power flows of each part of the system. This method provides great convenience for analysts and researchers to analyze the dynamic characteristics of the system and establish mathematical models. On the one hand, it has a clear and graphic one-to-one correspondence between the modular structure

of the power flow description and the physical structure of each part of the system itself as well as various dynamic influencing factors, which makes it easy to understand its physical meaning [66]; On the other hand, the description is aligned with the dynamic mathematical model of the system, and the number of equations of state of the system matches the number of energy storage elements. [67]. The corresponding mathematical model can be derived regularly from the Bond Graph of the system.

The Bond Graph itself has a set of strict descriptions of the transformation rules, which are highly harmonized with various typical physical properties and some general laws. Because of this, it provides a very effective way to accurately define and describe the dynamic model of a system and derive the state equations accordingly. In the meantime, the Bond Graph method provides lecturers and researchers with a solid and effective tool for Mechatronics subjects education. Both the concise representation of the Bond Graph and its interdisciplinary representation are convincing aids.

1.2.1 Application of Bond Graph

The Bond Graph can be applied in multiple fields to exhibit its unique synergy characteristics. The most common representation using Bond Graph is the mechanical, electrical, and hydraulic domains. The Bond Graph has synergy characteristics by modeling the multiple domains using the same graph. Compared with the traditional mathematical solution, the Bond Graph provides a graphical practical tool to solve the modeling and simulation.

The step of the modeling using the Bond Graph is shown in the following:

- Analyze the schematic
- Create the Bond Graph from the schematic
- Convert the Bond Graph to the block diagram
- Build the simulation program from the block diagram
- Finish the simulation

It is been introduced using traditional mathematics methods such as ODEs and state space over the past decades. The dissertation presents the Bond Graph as a unique

method to achieve the same simulation result as the mathematics method but with simple implementation and a straightforward relationship. The purpose of introducing the Bond Graph as a teaching method is not to replace the traditional method, but instead to help students understand the complex equations and relationships between the physical components. There are three categories in the Bond Graph, active elements, passive elements, and Junctions. The active elements can be considered as the input signals resources, the passive elements correspond to the consumed components in the dynamical system. And the Junction serves the purpose of connecting two elements, active elements to passive elements, or passive elements to passive elements.

The reason for introducing this innovative teaching method in the mechatronics engineering subject is to address the difficulties students face in understanding complex mathematical relationships. The Bond Graph could provide a clear picture of the whole connection in the kinematics and dynamics of the mechanical system. The potential and the kinetic energies are merged into the same Bond Graph without analyzing their relationship. [68]. The Bond Graph is crucial for vehicle and aircraft simulations, demonstrating its powerful capabilities in modeling mechanical systems. [69]. The visual representations in Bond Graph are quite distinct from traditional mathematical solutions. Traditional solutions present all the equations to show the relationships between components. In contrast, the Bond Graph representation is a graphical representation with bonds and arrows illustrating all the connection relationships.

Due to the complexity and diversity of engineering systems, a system not only involves a single form of energy but often a variety of energy forms of coupling. The current methods for analyzing system dynamics are often limited to a single energy domain of the system. In the case of integrated engineering systems with multiple energy forms, the Bond Graph provides a unified way to automatically realize the system dynamics modeling and simulation on the computer with effective global dynamic performance analysis [70]. The Bond Graph theory based on the principle of energy conservation can deal with the modeling and simulation problems of multiple energy forms in a unified way, which has the features of simple structure, large amount of information, and regularization of the dynamics modeling process [71]. The field of electrical engineering is well-suited for applying Bond Graphs, which offer clear relationships instead of complex equations. [72].

A very important property of the Bond Graph theory is that the structure of a system's state equations can be predicted based on the causality of the system's Bond Graph model before writing the system's state equations. Students and researchers could study the system equations by applying the Bond Graph [73]. The only basis for describing a system in a bond diagram is the interacting subsystems (or components, structures) in engineering and physical systems which could transfer the power as the original basis of the Bond Graph [74].

The Bond Graph theory has the following significant features compared with other dynamical methods summarized in the following:

- A unified approach of multiple energy domains of the system;
- Reveal the dynamics of the system intuitively in a concise graphical way;
- The system equation of state The system equations of state are established in a regularized way, which is convenient for the computer to generate the simulation program automatically.

1.2.2 Lagrangian Bond Graph

The Bond Graph has three representations in mechatronics engineering, the force simply presented by the passive elements; the dynamic motion relations illustrated by the combination of the bonds and the active and passive elements; and the last essential is the power, the exhibition of the power is the Lagrangian and Hamiltonian Bond Graph.

It is well known that analytical mechanics is based on the "least action principle ". It states that there is a state valuable that describes the state of the system, and its integral over time to be the evolution of the system state, which needs to satisfy the minimization principle [75]. This quantity can describe the condition of the system, whose parameters are required to be able to completely describe the state of the system. We call such a set of parameters that can completely and non-repeatedly describe the state of the system as generalized coordinates [76]. As for the second dynamic motion relations, starting from Newton's second law, which is convenient for solving simple plasma problems, but to solve complex problems, we have to use the "isolate body" method, list the equations one by one,

and solve the system of equations. Newton's method is suitable for specific descriptions. The Bond Graph relates to the 'power' coming up from Lagrange's mechanics, which provides a simple means of describing complex systems and a uniform law for solving problems [77], is based on a new mathematical method invented by Lagrange, called "analytics", which he called "analytical mechanics", and the basic variables of the Lagrange function are coordinates, velocities (coordinates) and speeds (coordinates), which are the same as those of the other equations. The basic variables of Lagrange's function are coordinates, velocity, and time [78].

The bond graph is useful for analyzing both mechatronics engineering and mechanical dynamic systems. In the mechanism dynamics system, the Bond Graph presents an effective graphical tool to present the physics of the system and obtain its lagrangian. By extending Nother's theorem and the Bond Graph, conservation law can be obtained for different energy domains [79]. And the Lagrange and kinematical equations can be derived from the generalized 1-junction, and the constraint 0-junction [80].

The Lagrange equations are often the fastest way to obtain the equations of motion for mechanical systems consisting of particles and rigid bodies constrained by reactive constraint elements. Lagrange's equations are also handy for mechatronics systems since a correct representation of the stored energy state functions ensures that the motion equations represent the process of energy conversion correctly [81]. Since the Bond Graph handles all forms of energy systems, the Lagrange equations can be applied to any system represented by the Bond Graph. The Bond Graph illustrates the synergistic characteristics by presenting the Lagrange equations in mechanism analysis.

1.3 Education in Mechatronics

Mechatronics is an interdisciplinary subject that requires students to master knowledge in multiple domains. In this case, students need to reach a certain level of knowledge in Mechatronics subjects. It needs some technique and skills to help students digest the concept of complex knowledge. Mechatronics education is a relatively new discipline in the field of engineering, with a history of 40-45 years [82]. The development structure of mechatronics is shown in Figure 1.2.

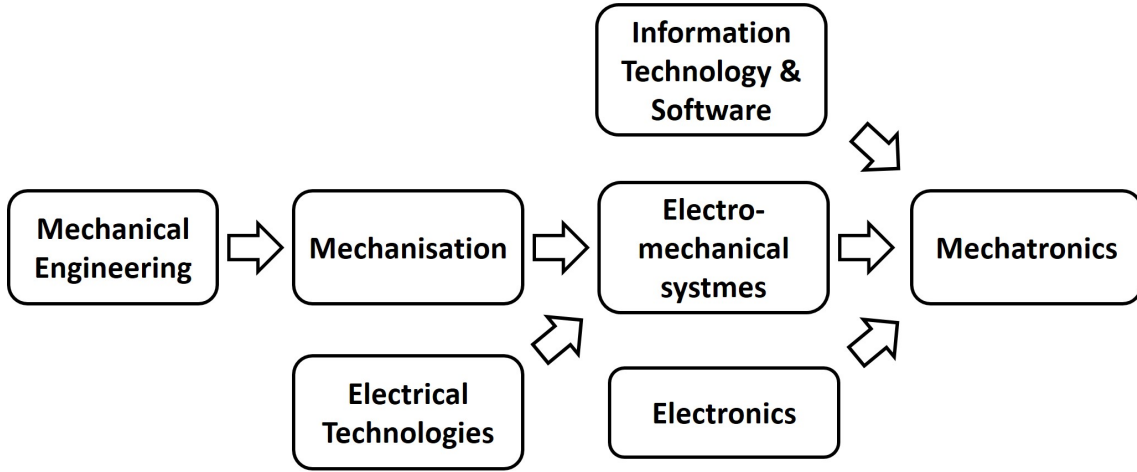


Figure 1.2. *Mechatronics evolution* [82]

In Mechatronics education, theory teaching emphasizes theoretical derivation and abstract principles, while practical teaching focuses on improving students' modeling and simulation skills. Both types of teaching need to be focused on together in order to realize the steady improvement of students' abilities [7]. In the process of teaching, universities impart knowledge and skills through the "theory-practice" model. However, despite acquiring theoretical knowledge, students still have no idea about modeling and simulation. In this case, the Bond Graph is proposed to provide students with a clearer grasp of the concepts in modeling and simulation.

The Mechatronics specialty is more practical, so when teaching mechatronics, professors can't just focus on theoretical knowledge but also give a full demonstration of the importance of practical teaching. The development of higher education has led to the introduction of many new teaching models. The Bond Graph can effectively meet teaching standards and applications. Diversifying teaching modes, modularized teaching, and collaborative education can significantly enhance students' learning ability and motivation.

The Bond Graph theoretical method helps students maintain their learning curves in the flow state. It is the responsibility of the professors to devise a method to keep students in the flow channel to prevent boredom and anxiety during the study in Figure 1.3. The Bond Graph method, combined with incremental case studies, provides the solution.

With the gradual improvement of the teaching reform program, many colleges and universities are adopting more mature teaching methods to promote student development

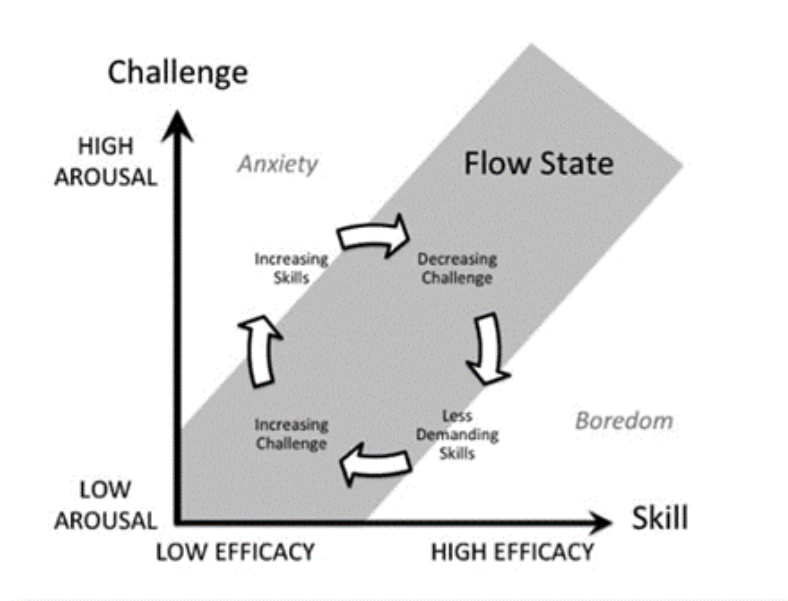


Figure 1.3. Relationship of challenge and skill, and the flow state [83]

[84]. The current stage of mechatronics teaching is analyzed, and the teaching program is designed with distinct modules: basic teaching modules, mechanical basic modules, electrical basic modules, and control basic modules. The text discusses modular teaching strategies specifically designed for mechatronics engineering. [85]. Theoretically speaking, there is more in line with the needs of modern society for mechatronics professionals. However, from the perspective of practical operation, the student's practical ability and theoretical knowledge are inconsistent with mastery, and it is difficult for them to adapt to the unpredictable industry market. It is apparent that to fully enhance teaching effectiveness, there is a requirement for a module that can integrate educational knowledge, and this method is the Bond Graph.

The direction of mechatronics education aims at the following contents [86]:

- Intellectualization is an important development direction for the development of mechatronics technology in the 21st century;
- Modularization is an important and difficult project;
- Due to the popularity of networks, the end devices for remote control are themselves mechatronic products.

- The system can be flexibly configured for any combination while seeking to achieve multi-subsystem coordinated control and integrated management.

There are several open issues for the education of Mechatronics. First of all, the Bond Graph provides the lecturer with a graphical language to catch students' eyes in the class. Second, Mechatronics engineering needs a relatively decent education to help students digest the knowledge. Third, the Bond Graph has the ability to enlarge the core content of modeling and simulation in Mechatronics engineering.

1.3.1 Graphical Language

The bond graph is a type of graphical language. The graphical language has most of the functions of Images. It stimulates visual pleasure, mobilizes all-round visual cognition, and at the same time triggers rich associative abilities and creative thinking. This generates sensory experiences and enables immediate understanding of the content. [87]. It is highly compatible with the audience's psychological desire and acceptance law and thus has irreplaceable advantages in value communication [88].

These are advantages of the graphical language in the following [89, 90]:

- Images are the most concise and fastest visual information communication language;
- Images are the most expressive visual language that can be easily recognized and remembered;
- Images are a world language that transcends national barriers

The Bond Graph as a visual language contains the main advantage of the graphical language, for this reason, the students could have easier communication and a better memory of the new contents.

Dataflow programming is a typical programming diagram that presents the directed data and energy flow between the operations [91]. There are several dataflow programming tools available for mechatronics engineering studies, with LabVIEW and Simulink being the most popular choices [92]. LabVIEW is chosen to be the platform for the demonstration in the dissertation because of its visual characteristics and the variety of functions integrated [93].

1.3.2 Bond Graph in Education

This dissertation proposes a unique teaching method, the Bond Graph method, for teaching the subject of mechatronics. From a mathematical point of view, Bond Graph is a graphical alternative to ordinary differential equations. Traditionally, control theory uses ordinary differential equations because control theorists are familiar with them. However, from a mathematical point of view, the two methods are equivalent but contain a slightly different approach in their application. Chapter Three will focus on the mathematical similarities between the two approaches while emphasizing the differences in graphical representation.

The Bond Graph was proposed as an integrated graphical tool for presenting synergistic effects in mechatronics engineering, which has been considered the right choice for educating students in system modeling for decades [94].

The Bond Graph in education has rapidly developed, the Bond Graph is proposed for linear modeling and extends for the general models easier in certain analysis [95]. A bioprocess simulation modeled using Bond Graph is stored in a database to assist master's students in bioprocess modeling and simulation [96]. The The Bond Graph plays a critical role in dynamic system analysis, which provides a common and handy tool for researchers, and in the meantime, the Bond Graph has become a priority tool for modeling and simulation in mechatronics engineering[97]. The Bond Graph is well-suited for creating an automated virtual lab for dynamic modeling. The Bond Graph tool has demonstrated its potential to be supplemental in system dynamics education [98]. The Bond Graph has established a solid background in economic modeling and chemical analysis from a graphical perspective [99].

Bond Graph is a graphical tool for representing the energy flows in a system. It concisely demonstrates the behavior of complicated systems. Bond Graph allows the unification of mechanical, electrical, and hydraulic systems [100] using the same tool. Combination diagrams play a vital role in the synergistic connection of mechatronics disciplines.

In China, the Bond Graph is a practical tool in many interdisciplinary fields, for instance, a wheel brake system was analyzed in [101], and the Bond Graph is implemented

to present the structure of the motor with inverter and gearbox in [102]. Based on the multiple domains modeling of the Bond Graph, it helps the simulation in modeling Marine Condenser [103]. The researches above are based on the application of Bond Graph and are limited to specific research in a single domain. Research across multi-domain and the significance of Bond Graph in education have not been given the corresponding attention. In summary, all the case studies of the Bond Graph emphasize that there is a huge application market in the future of Mechatronics engineering. The Bond Graph has a huge potential application in the Mechatronics education method.

1.3.3 Bond Graph Advantages and strategies in Mechatronics Education

Ideology serves as the essential foundation for action. Teachers and students should realize that the mechatronics engineering subjects are a one-subject combination of theory and practice, It's crucial to align theoretical knowledge and social practice with societal needs in order to promote the learning and teaching concepts. Mechatronics puts modeling and simulation into teaching, which is a deepening and development of the vocational task teaching method [84]. Mechatronics engineering students could gain 'modeling and simulation' experience from the experiment, not only from the class theoretical education. Mechatronics students understand that grasping the interrelation and holistic nature of the subject matter can enhance students' overall competence [104].

Utilizing the Bond Graph to accomplish teaching tasks has multiple advantages. Firstly, it improves the ability level of the educated person, and effectively improves his design ability, ability to adapt to different problems, and innovation ability; secondly, it improves the stress capacity of the educated person, and lets the educated person obtain economic and value orientation; thirdly, it improves the functional capacity of the educated person, that is to say, it improves his competence and ability to explain and show, and thus realizes the improvement of teaching effectiveness.

The modularization of the teaching is one of the strategies in the University of Debreceen, Engineering faculty, mechatronics department. The modularization of knowledge points, which is the focus of the study of modular pedagogy [105], places higher demands

on the teachers who organize the classroom in terms of lesson preparation. On the basis of mastering the teaching materials of the grade, teachers make cross-lesson preparations to understand the knowledge points of other grades and compare the similarities and differences with the knowledge points of the grade. Integration of knowledge points in each grade is carried out [106].

The next strategy applied to mechatronics engineering teaching is the graphical representation of the knowledge.

The last strategy is the synergy of mechatronics, which is the Synergistic integration of mechanical engineering, electrical engineering, and computer-based control. The definition of synergy is the interaction or cooperation of two or more organizations, substances, or other agents to produce a combined effect greater than the sum of their separate effects.

The application of engineering-learning integration in teaching practice has achieved good results. This teaching method has played a significant role in mobilizing students' learning enthusiasm and cultivating students' professional temperament. The vocational education mode of engineering-learning integration is especially suitable for teaching electromechanical specialties and has a broad development prospect.

In summary, the application of engineering integration in the teaching of electromechanical specialties is a new exploration of teaching practice, which is in line with the general law of theoretical and practical education. With the deepening of teaching reform, the application of engineering integration in teaching electromechanical specialties should gradually become a paradigm of vocational education, and play a greater role in cultivating the vocational skills of students, improving the quality of the labor force, and developing the comprehensive quality of educated people.

1.4 Beyond State of the Art

Mechatronics engineering is an interdisciplinary subject, that includes mechanical engineering, electronics engineering, and computing engineering. The term "mechatronics" is a combination of words from the front part of "mechanical" and the back part of "electronics". The word creation can be traced back to 1971 from a Japanese engineer [1]. The most common definition of modern mechatronics engineering is precision mechanical en-

engineering with synergy, high intelligent computing software, and modeling and simulation in the dynamical control system [107].

The dynamic system implies that the system's state changes over time. In dynamic control theory, there are various types of control systems, including nonlinear and linear control systems. [108]. The linear control system can be illustrated as the system obeys the theorem of the superposition, on the contrary, the non-linear control system does not follow the superposition theorem [109]. In the dissertation, the PID controller is proposed as a classic linear control system material, and the sliding mode controller is demonstrated as the teaching material for the nonlinear control system.

In the meantime, Mechatronics engineering combines multiple subjects with mixed domains, which makes the subject complex to digest for mechatronics engineering students. In the dissertation, a comparison of the numerical and analytical methods is presented to overcome the difficulties in mechatronics engineering education. The traditional method with complex mathematics calculations such as ordinary differential equations(ODEs), and state space can be considered as the numerical method, and the Bond Graph as a native graphical toolset can be considered as the analytical method in helping students understand the sophisticated concept of the Mechatronics engineering education.

The Bond Graph is a native language for mechatronics engineering researchers, and it provides researchers with a novel tool to combine multiple domains [8]. Ordinary differential equations(ODE) and state space are some traditional mathematical methods to solve the dynamic system in modeling and simulation assignments. With the help of the Bond Graph, the students and the researchers could simulate the dynamic system without using the traditional methodologies. Compared with the complex traditional mathematical methods, the bond graph could help students save calculating time to get the block diagram of the dynamic system efficiently.

1.4.1 Problem statement and Challenges

The control theory has been well-developed in recent years with the technology development. The control theory appears in the human's daily life. The modeling and simulation are considered critical processing in the control theory, both in the theoretic-

cal and the practical. For the traditional education in mechatronics engineering subjects, mathematics is essential for research and education.

Based on Mechatronics education in China, the experience can be concluded in the following. It is hard to understand and digest the concept of the complex mathematics theory. Then the Bond Graph is necessary for the students and teachers [110] [111]. The students could have a better understanding of the knowledge with the help of the Bond Graph and a quick solution to the questions. The teachers can have a graphical tool to present the dynamic control system from another perspective.

The Bond Graph can be considered as a handy graphical language to express the details from a visual point of view. In this case, the Bond Graph can assist students in understanding mathematics calculations, but it is not an alternative solution to traditional methods. The Bond Graph can apply to many fields, such as mechanical electrical, and hydraulic systems. This property of the Bond Graph presents the synergy of mechatronics engineering. The PID controllers, sliding mode controller, inverse, and direct disturbance observer can be represented using the Bond Graph. The Lagrangian Bond Graph provides an alternative method to express the complexity of the Lagrange equations.

Lastly, a three-year test has proven that the Bond Graph is more acceptable than the traditional mathematical method for mechatronics engineering students.

1.4.2 Future trends and Limitations

The dissertation proposes the Bond Graph as a practical teaching tool in Mechatronics Engineering. In the meantime, the PID and SMC Bond Graph representation are demonstrated in the dissertation. The disturbance observer and Lagrangian Bond Graph are presented in the dissertation to show the properties of the Bond Graph. With the rapidly developed AI technology, the ChatGPT and MathGPT can think like a human brain and it can "read" the content of the images. However, based on the test, the AI can only deal with a system in a single domain; when the system occurs in multiple domains, it provides either wrong information or irrelevant content. Artificial intelligence technology still has much to improve regarding image understanding and processing.

Due to the limited time and effort during the study, the following contents can be

regarded as future trend research topics that are not covered in the dissertation.

- Neural networks can be a handy tool for data processing with plenty of parameters, such as the selection of the sliding mode controller parameters, and the disturbance observer parameters process.
- The teaching activities focused on modeling and simulation instead of the real experiment. Experimenting with a real DC electrical machine can be the future task to continue the dissertation.
- Radar technology is increasingly popular in future technological confrontations. The application of radar technology in the mechanical and circuit directions is a wise decision.

1.4.3 Novelty and Contribution

This section starts with a brief introduction to the Novelty and contribution to the dissertation.

- First, the dissertation introduces the Bond Graph as a novel teaching method in the mechatronics engineering subject, it can emphasize the synergy among the subjects. It is a native graphical language for researchers and mechatronics engineers.
- Second, it brings up the Bond Graph representation of the PID controllers, sliding mode controllers, and the Lagrangian expression.
- Thirdly, the direct and inverse disturbance observer can be expressed by the Bond Graph.

1.4.4 Main Structures of the Dissertation

Mechatronics Engineering is a complex subject because of the multi-domain concept. It is responsible for the professors to figure out a novel education method suitable for the complex Mechatronics engineering subjects. In the meantime, it is critical to accelerate the learning curve for students' study process. In this case, the dissertation proposes

the Bond Graph as a novel education method in Mechatronics engineering to solve the above-mentioned problems.

Chapter One focuses on the literature reviews. First, section 1.1 introduces the background of Mechatronics engineering, the importance of the dissertation research topic, and the control theory application for the background of the case study. Second, sections 1.2 and 1.3 introduce the basic concept of the Bond Graph and education in mechatronics engineering. It illustrates the critical role Bond Graph plays in the Mechatronics engineering education. Next, section 1.4 presents the state of the art of the dissertation. Section 1.5 is the Methodologies in the dissertation and Section 1.6 shows the Terminologies appearing in the literature review.

Chapter Two illustrates that the Bond Graph benefits the education method in Mechatronics engineering. The whole chapter could be divided into two parts, the first part can derive to THESIS ONE, and the second part leads to THESIS THREE. The first part is from subsection 2.1 to 2.3, the Bond Graph is proposed as a novel education method in Mechatronics engineering. The Bond Graph simplifies mechatronics modeling teaching methods for undergraduate students by combining modular design and visual programming language with multiple case studies. The main contribution is accomplished by the last case study in subsection 2.3, the Bond Graph is recognized as an effective graphical tool for teaching PID and sliding mode control in Mechatronics.

The second part leads to THESIS THREE, subsection 2.4 proved that the Bond Graph benefits the education method in Mechatronics and also provides a simple alternative method to traditional energy of spatial dynamics. In the meantime, Bond Graph is to modularize the modeling and simulation and enhance mechatronics education by representing traditional formulas visually.

Chapter THREE leads to THESIS TWO, first of all, case studies of the inverse and direct disturbance observer demonstrate the powerful graphical representation of the Bond Graph. Compared with the inverse disturbance observer, the direct disturbance observer has better performance without the additional filter. The Bond Graph provides a unified graphical module representation for these two disturbance observers, enhancing the effectiveness of mechatronics education.

Chapter FOUR focuses on the test results, a three-year test finding from the mecha-

tronics engineering students has proved the effectiveness of the Bond Graph in the Mechatronics education method.

1.5 Methodologies in Dissertation

The traditional mathematical equations result in input and output relations. It also describes how the system operates in multiple domains. The introduction of the basics of the Bond Graph provides a generalized tool to analyze multiple dynamic systems. There are several methodologies in the dissertation, which will be introduced in these categories in the following:

1.5.1 Bond Graph

There are three branches of the bond graph elements, passive elements, active elements, and junctions. The passive elements contain 1-port element relating the power and energy variables.

1.5.1.1 Arrows and Causality in Bond Graph

The arrows are the essential characteristics of the Bond Graph. It describes the energy flows among all elements' relationships. The arrows are considered as the flow energies around the node in the block diagram. The nodes are represented by the passive 0 and 1 junction in the Bond Graph.

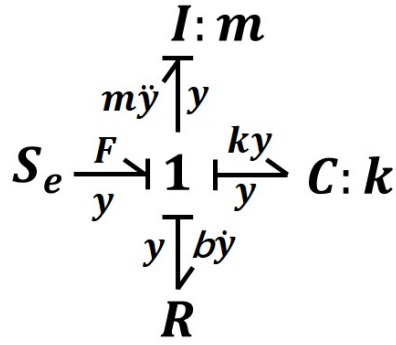
The causality donates another property of the Bond Graph. The causality is the direction of the effort's source, which decides whether the relation is integral or differential. The distribution of the causality is based on the circumstance of the dynamic system. It is suggested that integral causality is the preference in the Bond Graph modeling.

1.5.1.2 Kirchhoff's Circuit Law

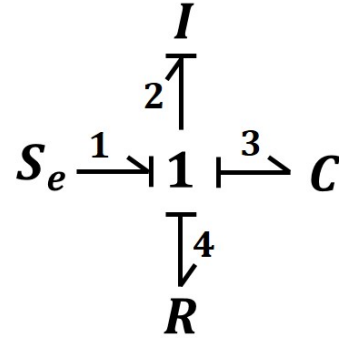
Kirchhoff's Circuit Law is a basic principle for solving problems under the circumstances of the electrical circuit[112]. Kirchhoff's Circuit Law is applied as a unique principle in Bond Graph modeling. The active element, junction, and passive junction represent

the voltage resource, nodes, and compliance respectively, which consist of the simple Bond Graph of a dynamic system [1]. Kirchhoff's Circuit Law is well applied because of the synergy property of the Bond Graph.

A simple Bond Graph is demonstrated in the following Figure 1.4. Figure 1.4 (a) shows the Bond Graph with the mathematical relation of the dynamic system. The numbers above arrow in Figure 1.4 (b) is convenient for the modeling in the following:



(a) The Bond Graph with the relations



(b) Bond Graph of mass spring damper system

Figure 1.4. The schematic and the Bond Graph of the mass-spring-damper system

First, make all the arrows in a sequence.

Second, check the junction type in the Bond Graph. Since it is a 1 – junction in the Bond Graph, then do the summation of the effort.

Third, make the relation between all the elements based on Kirchhoff's Circuit Law. The sum of the inputs is equal to the sum of the output, which is decided by the direction of the arrows.

$$e_1 = e_2 + e_3 + e_4 \quad (1.1)$$

The fourth step, check the causality in the Bond Graph to make sure the real output of the dynamic system. The causality is the direction of the effort. In Figure 2.6 (b), the e_2 is the output.

$$e_2 = e_1 - e_3 - e_4 \quad (1.2)$$

The relation shown in the equation 1.2 is the key to converting the dynamic system into the block diagram using Bond Graph modeling simulation. The complex Bond Graph analysis is based on the steps above logically.

1.5.1.3 Newton's Law and Lagrangian Bond Graph

There are two layers for the Bond Graph to represent, effort and force are introduced as the first layer, and the energy representation using the Bond Graph is the second layer.

For the first layer, Newton's second law of motion concerns the behavior of all unbalanced objects in dynamic systems. Since the Bond Graph is a graphical language to analyze the dynamic system, Newton's second law of motion is one of the analysis methods. Newton's second law and physics analysis are the main tools in Bond Graph modeling. Because of the synergy in the Bond Graph, the Bond Graph is introduced in electrical circuits and the mechanical dynamic system.

For the second layer, energy analysis in the Bond Graph is still a developing technology. The Lagrange plays an important role in the mechanism domain. Lagrange's equations are a powerful method for the modeling in many fields. Lagrange's equations can represent the energy and power involving only generalized displacements and velocities. The Bond Graph is also a powerful tool in modeling subjects by the graphical language of the energy storages and the effort flows.

The Bond Graph donates a unique analysis of the Lagrange equations mechanism. There are two sources of effort as the inputs, which are the two independent generalized coordinates. In the meantime, the passive element is the compliance. The Lagrangian Bond Graph above is detailed but complicated, so it is necessary to introduce a simplified version. This simplification version is the compliance field or C-field. The Inertance field shares the same logic as the compliance field.

1.5.2 T-Test

The most common application of a t-test is a statistical test of whether two sets of values are significantly different. First, the student's grade samples conform to the normal distribution population. Second, the samples of the grades are random samples. Third,

the t-test is well performed when the sample size is small. In sum, the t-test is a suitable tool for the analysis of the two groups of grades.

1.6 Terminology

Numerical and Analytical

In the dissertation, numerical means the traditional methods such as the ordinary differential equations, and state-space mathematical calculation. Analytical means the Bond Graph, which provides a graphical method to present the modeling and simulation.

Bond Graph

The Bond Graph is a native language for mechatronics engineering researchers, the Bond Graph is proposed as a novel mechatronics education method to accelerate the students' learning curve in Modeling and simulation.

The advantages of bond graphs are as follows: The graphical language of Bond Graph is easy for students to understand; it has A low threshold for mastery; It is mature for application in multi-domain systems. Disadvantages: The ease of mastery may lead students to rely on Bond Graph.

Traditional education method

In the dissertation, the traditional education methods are ordinary differential equations and state-space mathematical calculation.

Advantage: They are the underlying logic of modeling and the foundation for solving modeling problems. Disadvantages: High entry threshold; requires multidisciplinary knowledge; complex calculations.

Multi-domain system

Mechatronics engineering is an interdisciplinary subject, which requires multi-domain knowledge to solve problems. With the development of science and technology, the demand for multi-domain research is increasing.

Advantages: Each domain could be handled selectively in the multi-domain based on the different requirements; The multi-domain is flexible enough to accommodate domain extensions; Disadvantages: increased complexity; Data consistency issues;

In the modeling and simulation, the Bond Graph method provides a solution to solve the disadvantages of the Multi-domain. Modularization of Bond Graph can solve the complexity problem of multiple domains, and the synergy of Bond Graph can solve the Data consistency issues in multiple domains. Efficient application method usages are characterized in the field of Bond Graph applications in the multi-domain system.

Adaptive Robust control System

Adaptive robust control is a control method designed to handle uncertainty and changes in the system. The adaptive robust control is one of the case studies to present the efficiency of the Bond Graph. The Bond Graph method is used to represent the adaptive robust control in the case study because of the synergy adjustment in multi-domain. The benefits of the Bond Graph are demonstrated in the case of the adaptive robust control representation using the Bond Graph.

Inverse Disturbance Observer and Direct Disturbance Observer

An inverse disturbance observer uses the inverse model of the system to estimate disturbance, on the contrary, the direct disturbance observer uses the direct model to estimate the uncertainty without relying on the additional filters. The inverse disturbance observers are suitable for systems with large model uncertainties, while direct disturbance observers are more suitable for accurate control systems.

The inverse and direct disturbance observer representation using the Bond Graph proved that the Bond Graph is a top-level graphical programming tool in Mechatronics Engineering education, in chapter 3.2.

2

Bond Graph Benefits in Mechatronics Engineering Education

The Bond Graph is an effective graphical method for depicting the dynamic behavior of physical systems across various domains. The bond graph provides a unique approach to system modeling, enabling mechatronics engineers to effectively capture both the efforts and flows within a system. The relationships are depicted through active and passive elements, bonds, junctions, making bond graphs an effective graphical tool for modeling interdisciplinary subjects in mechatronics engineering systems.

The numerical methods are the traditional mathematical methods, such as Ordinary Differential equations (ODEs) and state-space. On the contrary, the Bond Graph is the analytical method in the mechatronics education method.

2.1 Bond Graph Benefits Education in Mechatronics

The Bond graph is not only useful for understanding existing systems but also for designing and simulating new mechatronic systems. With the help of the Bond Graph, the complex concept becomes more acceptable for the mechatronics students in their daily study and future research.

Education in mechatronics engineering benefits significantly from this aspect, as it

allows students to gain practical experience in the design and analysis of complex systems.

The bond graph is a graphical alternative to ordinary differential equations from a mathematical standpoint. Traditionally, control theory employs ordinary differential equations, as they are familiar to control theorists. However, mathematically, both approaches are equivalent but require a slightly different approach in their application. The first claim of the dissertation highlights the mathematical similarities between the two approaches while emphasizing the distinctions in graphical representation.

The bond graph could represent the PID controller and Sliding mode controller in the control design. The bond graph demonstrates a graphical combination of the various controllers and plants.

The proof is presented that mechatronics engineers achieve superior outcomes when utilizing the bond graph approach, based on test results from undergraduate students. The final test from the “Modeling and Simulation” course is evidence that using the bond graph method is easier than using the traditional mathematical technique to solve the mechatronics system. Meanwhile, a t-test is performed to help determine whether there is a significant difference between the bond graph solution and the ODE solution. In general, the significance level of the t-test is chosen to be 0.05, and the final t-values show that the bond graph solution and the ODE solution have a significant difference. It proves the bond graph method is more acceptable for mechatronics undergraduate students.

In this chapter, the Bond Graph will be introduced in the following categories: the basics of the Bond Graph, the application of the Bond Graph, and the Lagrangian and Hamiltonian Bond Graph. The basics of the Bond Graph chapter include all the fundamental elements and the operating concepts behind the graphical tool. The application of the Bond Graph chapter illustrates the dynamic system and the control theory representation with basic machine models. The Lagrangian and Hamiltonian Bond Graph chapter presents another powerful methodology for modeling, which could provide a clear blueprint from another graphical perspective.

2.1.1 Analytical Method: Basic of the Bond Graph

The traditional mathematical equations result in input and output relations. It also describes how the system operates in multiple domains. The introduction of the basics of the Bond Graph provides a generalized tool to analyze multiple dynamic systems.

There are three branches of the bond graph elements, passive elements, active elements, and junctions. The passive elements contain 1-port element relating the power and energy variables. There are three categories in the 1-port passive element, which are the R-element, C-element, and I-element. R, C, I elements with causalities are shown in Figure 2.1.

The Following is the 1-port list and its characteristics:

- R-element: The characteristic is related to the effort and flow directly.
- C-element: The basic elements could store the potential energy. It relates effort to generalized displacement directly.
- I-element: The basic elements could store the kinetic energy. It relates momentum to flow directly.

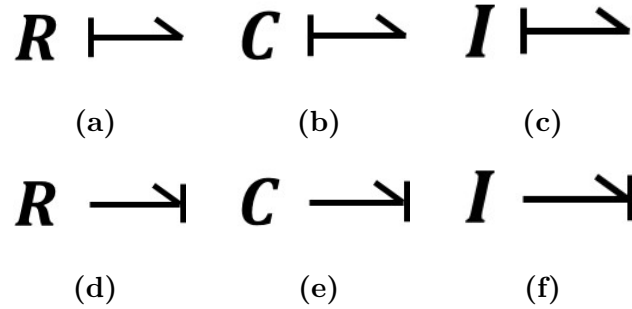


Figure 2.1. *R, C, I elements with causalities: (a) R with flow in; (b) an integral bond graph of C; (c) a derivative bond graph of I; (d) R with effort in; (e) a derivative bond graph of C; (f) an integral bond graph of I*

The active elements include the source of effort and the source of flow, Figure 2.2 shows the source of the effort and flow with the causalities, which presents the direction of the effort. The direction of the flow is opposite to the direction of the effort.

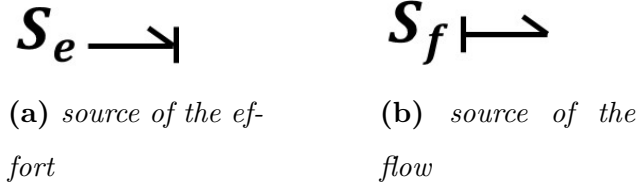


Figure 2.2. *Source of the effort and flow*

There are two categories of the junctions, which belong to the 2-port elements. The 0-junction and 1-junction are connected to the basic elements, and the transformers (TF) and Gytrators (GY) are the junctions converting the energies. The 2-port junctions like 1-junction 0-junction, TF and GY junctions with causalities are shown in Figure 2.3 and 2.4.

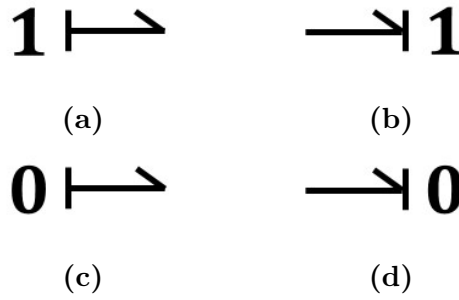


Figure 2.3. *4 different situations of the 1 and 0 junctions*

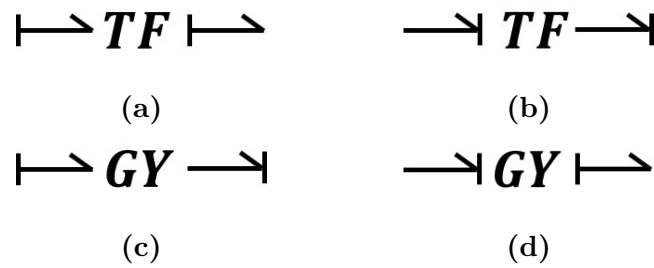


Figure 2.4. *TF and GY junctions with causalities*

The Bond Graph is a graphical representation for analyzing and modeling the dynamic behavior of the physical system. The Bond Graph can provide a systematic and unified method to describe the energy flow within a system, here are the basic concepts of the

Bond Graph. The arrow and the causality in the Bond Graph donate critical function, introduced in subsection 2.2.3

- Elements: passive elements represent source of the effort and source of the flow, it indicates the exchange of energy between elements. Active elements represent the basic physical components of a physical system.
- Bonds and arrow: The bonds connect the active elements and passive elements, which represents the flow of energy between them. The arrow represents the energy's flow.
- Junctions: 0-junctions share the common effort, the sum of the flows into the 0-junction equal to the sum of the flows out. 1-junction represents the conservation of effort. It shares the common flow.
- Causality: The casualty represents the direction of the effort on a bond, and the direction of the flow is opposed to the effort.

The constitutive relations of the R, C, I elements are shown in Table 2.1. The R elements show the linear systems' relationship and the C and I elements depict the integral connections of the components within the system.

Table 2.1. *Constitutive relations for R, C, I [28]*

R,C,I Constitutive relations	R	C-integral	I-integral
Generalized	$f = \frac{e}{R}$	$e = \frac{\int f dt}{C}$	$f = \frac{\int e dt}{I}$
Translational	$v = \frac{F}{b}$	$F = k \int v dt$	$v = \frac{\int F dt}{m}$
Rotational	$\omega = \frac{\tau}{\beta}$	$\tau = \kappa \int \omega dt$	$\omega = \frac{\int \tau dt}{J}$
Electrical	$i = \frac{e}{R}$	$e = \frac{\int i dt}{C}$	$i = \frac{\int e dt}{L}$
Hydraulic	$Q = \frac{P}{R_f}$	$P = \frac{\int Q dt}{C_f}$	$Q = \frac{\int P dt}{I_f}$

The elements in a Bond Graph can be summarized as follows: passive elements transform received power into either dissipated or stored energy, while active elements generate and supply power to the system. The purpose of the junctions is to connect various components of the systems. The branches are illustrated in the figure 2.5.

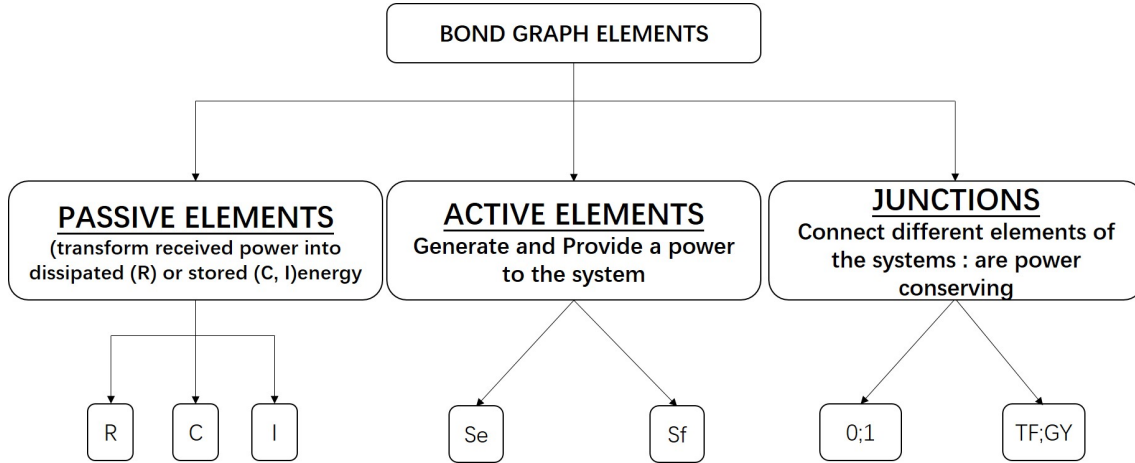


Figure 2.5. *Bond graph elements*

2.1.2 The Four Levels in the Bond Graph Representation

There are four layers of the Bond Graph, which are based on the levels of modeling. The Bond Graph serves as a graphical tool for this purpose. There are four levels of modeling: Technological, Physical, Mathematical, and Algorithmic [113].

- **Technological:** This level constructs the system's architecture by assembling various subsystems, which are the components of the plant. The technological level can be illustrated using the bond graph.
- **Physical:** The modeling employs an energy-based approach to describe the physical phenomena, the bond graph serves as a universal language for all domains of physics.
- **Mathematical:** The system's behavior is represented through mathematical equations.
- **Algorithmic:** This level pertains to a step-by-step calculation process known as an algorithm.

The Four Levels in the Bond Graph Representation are the same concepts as the modeling. Each of the contents corresponds to the modeling but with a real physical meaning and representation. The four levels of the Bond Graph are shown in the sub-items in the following. The physical level could be represented by using the elements and relations of physical systems. The mathematical level in the Bond Graph is the dynamic equations of the models. The algorithmic level of the Bond Graph could be illustrated by the Bond Graph causalities.

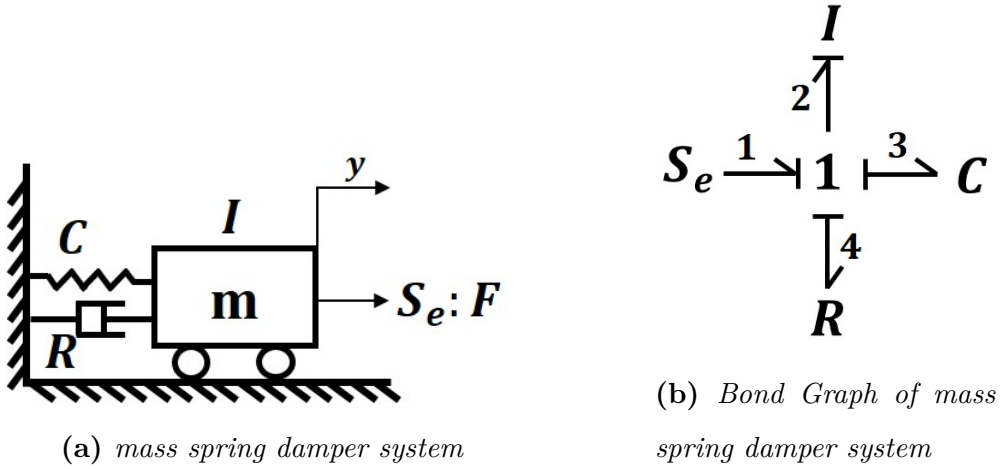


Figure 2.6. The schematic and the Bond Graph of the mass-spring-damper system

- Technological level: it is used to be the representation of the dynamic systems. The schematic and the Bond Graph of the mass-spring-damper system are shown in Figure 2.6(a) and (b) respectively.
- Physical level: the bond graph could represent the physical elements.
- Mathematical Level: Dynamic equations can be deduced from the Bond Graph graphical model. In the meantime, the Bond Graph with the relations of the components is shown in Figure 2.7.

The Bond Graph represents the Figure 2.6 equation in the following:

$$F - ky - b\dot{y} = m\ddot{y} \quad (2.1)$$

Table 2.2. *Bond Graph represent physical elements*

Domain	R	C	I
Generalized	$R = e/f$	$C = q/e$	$I = p/f$
Translational	b , damper constant	$1/k$, spring compliance	m , mass
Rotational	β , rotational constant	$1/\kappa$, rotational compliance	J , rotational inertia
Electrical	R , resistance	C , capacitance	L , inductance
Hydraulic	R_f , Hydraulic resistance	C_f , Hydraulic capacitance	I_f , hydraulic inertia

- Algorithmic level: it shows the simulation program using the causalities assignment. Based on Figure 2.6(b), the causalities could present the relation of all the components following these steps. The 1-junction means the common flow, which is the velocity in the demonstration. The effort calculation needs to be done using Kirchhoff's circuit law. The sum of the inputs that go into the node is equal to the sum of the output: $e_1 = e_2 + e_3 + e_4$. And then check out the real output in the Bond Graph with the direction of the causality. The e_2 is the output of the block diagram in Figure 2.6(b).

In this chapter, a short and detailed introduction to the basic Bond Graph with the 1-port element, 2-port element, and the multiple junctions are demonstrated. The Bond Graph helps in digesting the complex traditional mathematical equation with a graphical point of view. Compared with theoretical knowledge, the graphical method is designed to help memories of the complex contents. With the basic knowledge of the Bond Graph, the mechatronics students could have a better view of the dynamic systems with a different perspective.

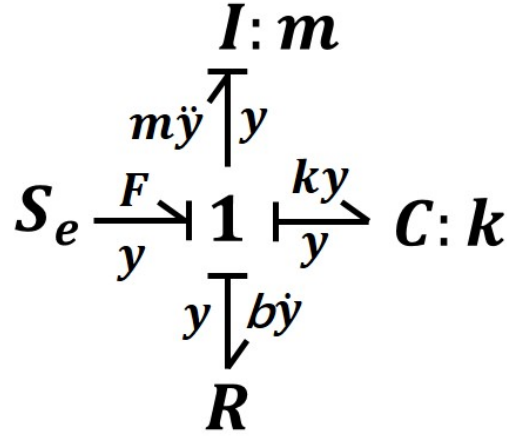


Figure 2.7. *the Bond Graph with the relations*

2.2 Bond Graph Application Modeling Method

The Bond Graph assists mechatronics engineering students in both theoretical education and practical analysis of dynamic systems. In this chapter, Several classical demonstrations begin with a simple DC motor model using Bond Graphs. DC machine speed control is implemented using a PID controller for educational purposes. The sliding mode controller for DC machine speed control demonstrates nonlinear control within the system. The final section represents hydraulic control using the Bond Graph.

The Bond Graph helps to apply in multiple domains, which makes it a powerful graphical language for the modeling and simulation field. It is not only for education purposes but also for improving the efficiency of the research.

2.2.1 DC Electrical Machine Numerical Representation

The teaching strategy aims to simulate linear systems technology for mechatronics engineering students. The DC machines serve as an effective model due to their reliable behavior in elementary linear control systems. The schematic of the DC electrical machine is shown in Figure 2.8.

An "ideal motor" connects the electrical and mechanical components, featuring a voltage source, an inductor, and a resistor in series within the electrical circuit. The

mechanical component includes the bearing and winding, along with their moments of inertia.

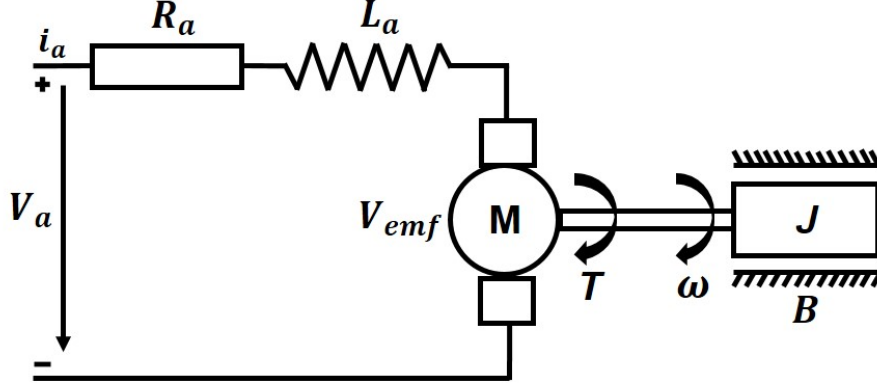


Figure 2.8. The model of the DC electrical machines [113]

the DC electrical machines mathematical model is depicted in following:

$$L \frac{di_a}{dt} = V_a - R * i_a - k_e * \omega \quad (2.2)$$

$$J \frac{d\omega}{dt} = k_m * i_a - B * \omega - T_L \quad (2.3)$$

Where ω (rad/s) shows the speed of the DC motor, i_a (A) donates the armature current, V_a (V) and T_L present the armature voltage and the load torque respectively. R (Ω), L (mH) are the terminal resistance and the terminal inductance in the DC motor mechanical part. J (gcm^2) and B (Nms/rad) illustrate the rotor inertia and the viscous friction in the DC motor electrical part. k_e (Vms/rad) and k_m (mNm/A) are the gains of the electrical and mechanical parts.[53]

2.2.2 DC Electrical Machine Analytical Representation

The mathematical model of the DC electrical machine is illustrated using ordinary differential equations. (ODE)(2.2)(2.3). The bond graph that integrates mechanical and electrical components is displayed in the following figure 2.9. The red half arrow indicates the direction of effort and flow. Causality represents the direction of the effort, while the flow direction is opposite to the effort.

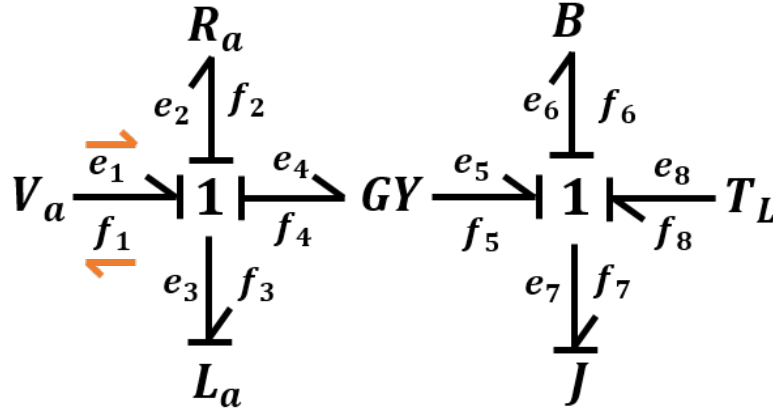


Figure 2.9. Bond Graph of the DC electrical Machine [113]

The Bond Graph of the DC machine illustrates the connection between mechanical and electrical components through a gyrator junction, as energy is converted from one form to another. There are common flow patterns at the 1-junction of the DC machine. After being created from the schematic of the dynamic system, the block diagram of the DC machine can be converted from the Bond Graph. It is depicted in Figure 2.10. The block diagram in LabVIEW is shown in Figure 2.11.

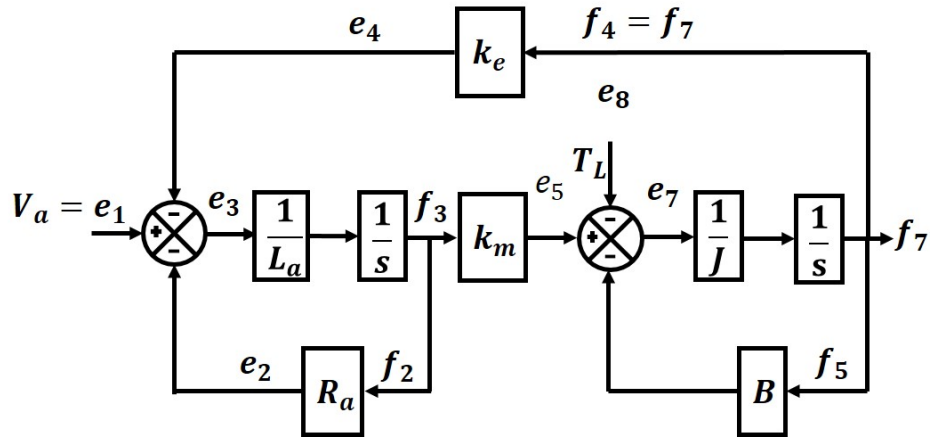


Figure 2.10. Block diagram derived from the simple DC electrical Machine

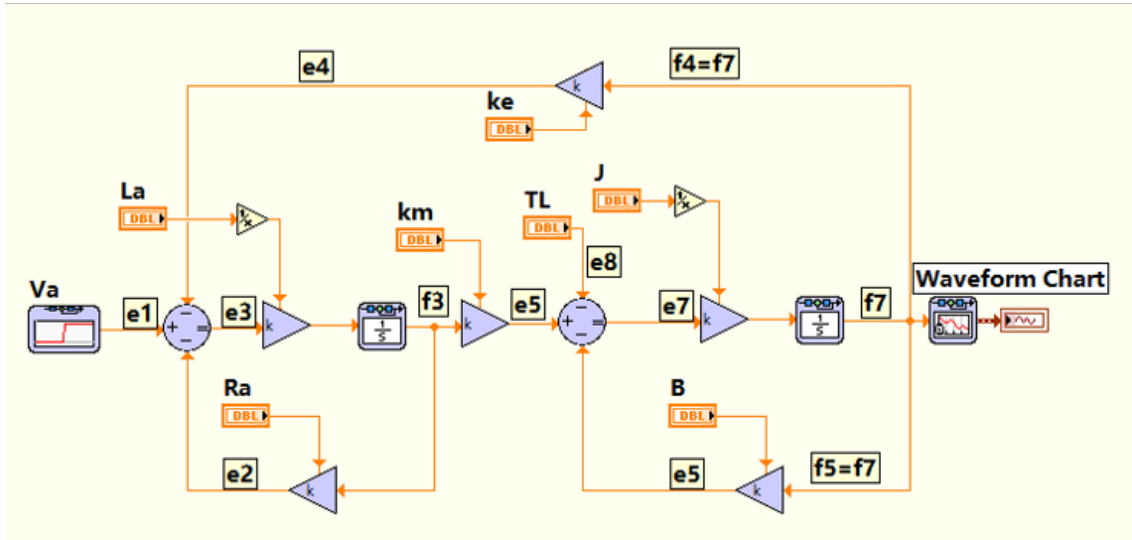


Figure 2.11. Block diagram of DC electrical machine in LabVIEW

2.2.3 DC Electrical Machine vs DC Electrical Generator

The Figure 2.9 shown above is a typical DC electrical machine Bond Graph. V_a donates the voltage in the electrical circuit, R_a and L_a are the resistor and inductor in the circuit. GY represents the rotor in the DC electrical machine, B and J are the bearing and inertia in the mechanical system. T_L is the torque load.

Notice the direction of arrows around the GY , the representation of the Bond Graph means different if the arrows' directions are changed. The Figure 2.12 is shown in the following:

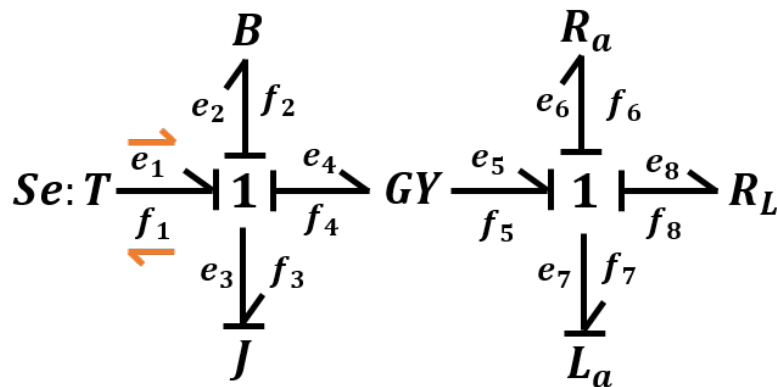


Figure 2.12. Bond Graph of Generator

The arrow of the Bond Graph represents the energy flow, and the causality of the Bond Graph donates the method of the calculations of the dynamical system. It will be introduced by comparing the DC Electrical Machine in Figure 2.8 vs the DC Electrical Generator in Figure 2.13.

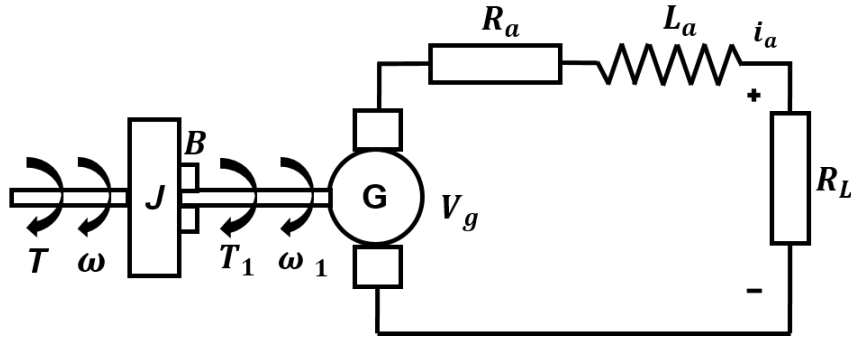
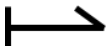
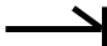
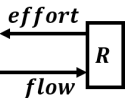
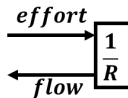
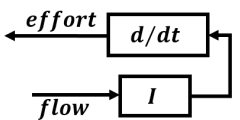
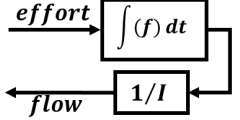
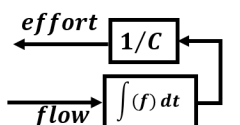
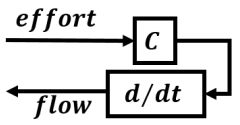


Figure 2.13. *A Simple Generator*

The T with ω in Figure 2.13 is the generator input torque with the angular velocity. The DC electrical machine converts the electrical energy into mechanical energy and the generator converts the mechanical energy to electricity energy.

Table 2.3. *Direction of the Bond Graph Causality*

		
R		
I		
C		

The Bond Graph of the generator is shown in Figure 2.12, which shares similarity to

the Bond Graph of the DC electrical machine Figure 2.9. The input of the DC electrical machine is the voltage, and the input of the DC generator is the torque. The voltage in the electrical circuit and the torque in the mechanical domain are the source of the effort. e_1 is the torque in the mechanical domain as input with the f_1 as angular velocity.

The arrow of the Bond Graph represents the energy direction, which decides the energy conversion between different domains. In the meantime, the causality represents the direction of the effort, which shows the different calculations in Table 2.3.

Each position of the causality represents one calculation, R elements have the division and the multiply; the C and I have the differential and integral with the different positions. In the meantime, the block diagram of the generator is converted from Figure 2.12.

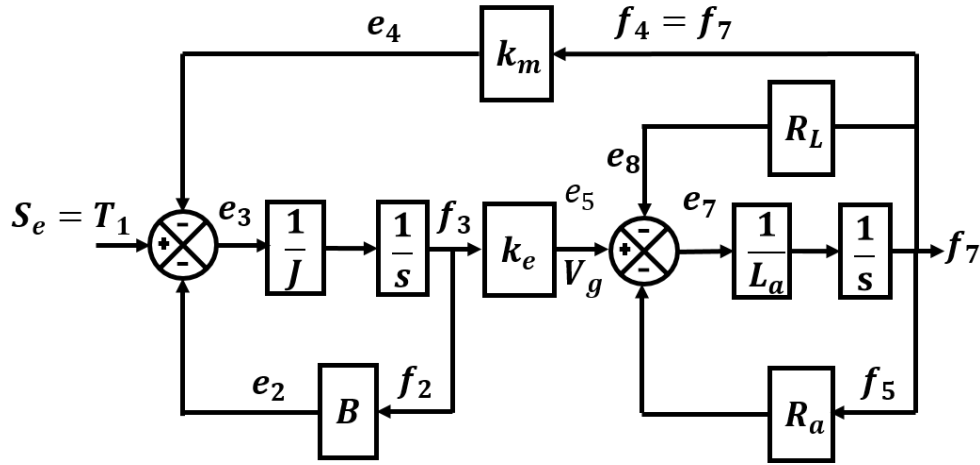


Figure 2.14. *Block diagram of the generator*

It can be concluded that the causality and the bond arrows and the causality play critical roles in the Bond Graph. The same representation can display different dynamic systems in multiple domains. In the meantime, the performance of the Bond Graph with different causalities is significantly different.

2.2.4 Simple DC Electrical Machine Speed Control Using PID Controller

In the control theory, the linear controller is an essential method for mechatronics students. A PID controller as a linear controller is depicted as a teaching resource. The

PID controller algorithm is straightforward and well-adapted in a variety of applications. The mathematical equation of PID is defined as follows:

$$u(t) = k_p * e(t) + k_i * \int_0^t e(\tau) d\tau + k_d * \frac{de(t)}{dt} \quad (2.4)$$

Based on the equation 2.4, the $e(t)$ is the difference between the reference and the output. The step response of the simulation depends on the parameters. k_p , k_i , and k_d donate the proportion gain, integral gain, and derivative gain respectively. The Bond Graph of DC machine speed control with the PID controller is called the active block diagram presented in Figure 2.15.

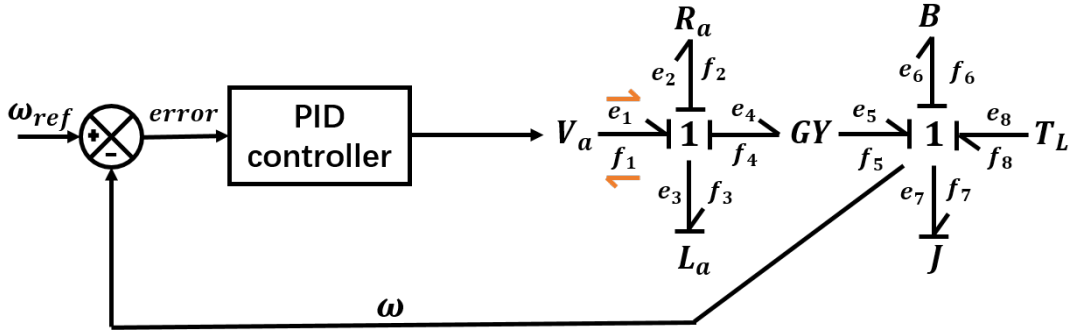


Figure 2.15. Block diagram of the PID speed control using active Bond Graph

The motor Maxon A-Max 26(110961) is the parameters reference of the Figure 2.15 simulation. The real motor parameters are in Table 2.4.

The programming in LabVIEW of the DC electrical machine speed control using PID controller is presented in Figure 2.16.

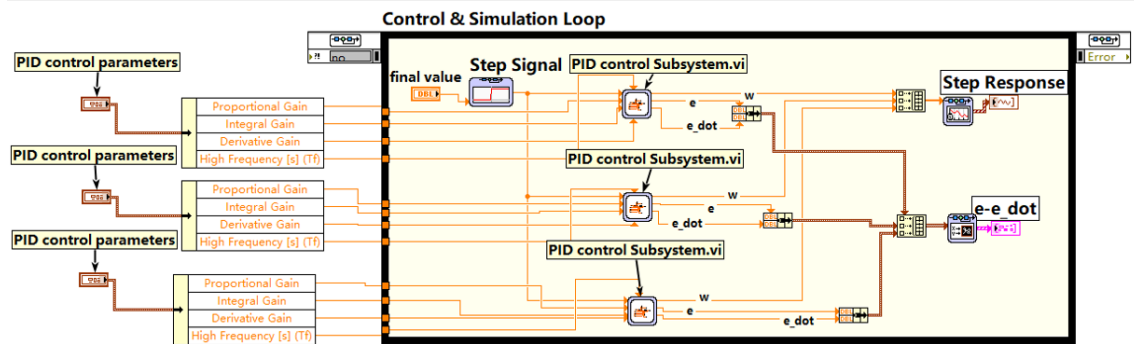


Figure 2.16. PID speed control using LabVIEW

Table 2.4. *PARAMETERS OF MAXON A-MAX 26*

Maxon A-max 26(110961)	
Nominal torque	17.4mNm
Nominal current	1.08A
Terminal resistance	3.13 Ω
Terminal inductance	0.333mH
Mechanical time constant	14.7ms
Rotor inertia	13.2gcm ²
Torque constant	16.8mNm/A

The step response of the DC machine speed control using PID control with different parameters k_p in Figure 2.17. The increase of the step response overshoot reflects on the increase of the k_p . The response time is opposite to the overshoot increase, when $k_i=0.2$, and $k_d=0.01$.

Trajectory e and $\dot{e}$ can illustrate the convergent performance of different k_p in the following Figure 2.18. The trajectory shows the relationship between the velocity error and the position error. Both of the errors converge to zero in a limited finite time. The convergence rate decreases with the increase of the parameter k_p .

After the introduction of the linear PID controller, one of the nonlinear controllers is needed to compare with the linear PID controller. The sliding mode controller is a simple one among the nonlinear controllers, which is complex enough to understand and simple enough to apply.

Step response

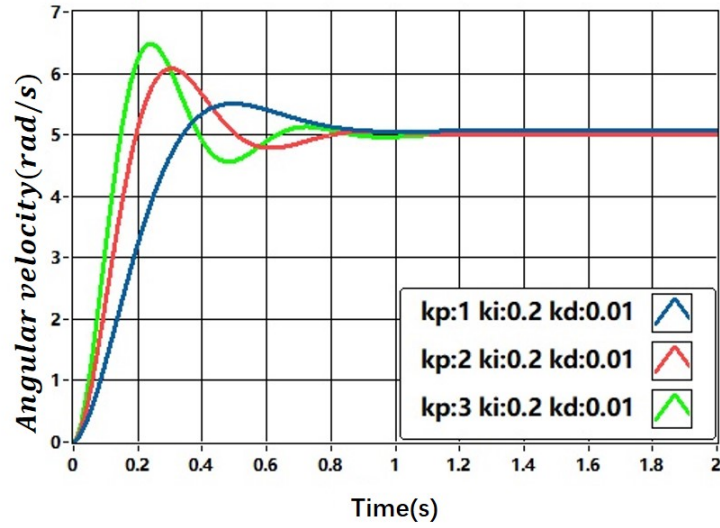


Figure 2.17. Step response of the PID controller with different k_p

$e - e_{dot}$

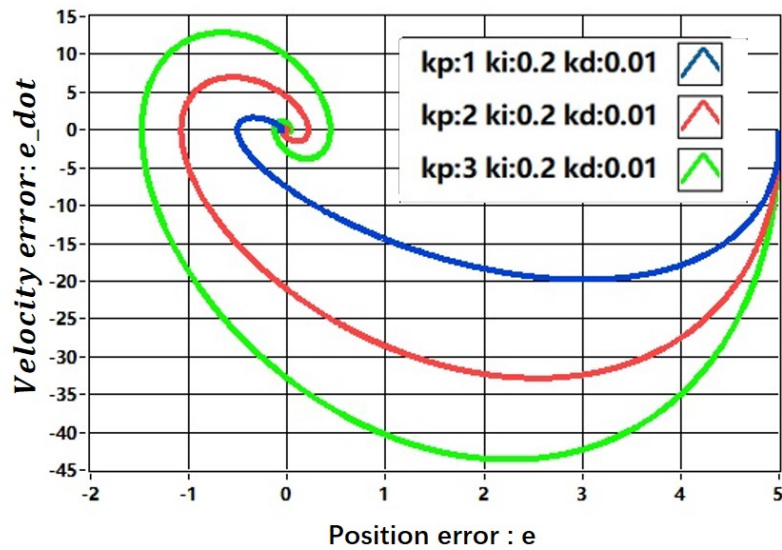


Figure 2.18. e and $\dot{e}$ of the PID controller with different k_p

2.2.5 SMC Controller Speed Control Applied on DC Electrical Machine

For mechatronics engineering students, the study of the nonlinear system is carried out with the prerequisite of grasping the linear systems. Another teaching strategy is to focus on designing technologies instead of learning technologies for mechatronics engineering students. We propose a teaching method called modular teaching, which divides the knowledge contents into modules. The pieces of the module content make the knowledge easy to understand. It is the final step to gather the modules to consist of the blueprint of the whole knowledge picture. The upgrade demonstrated DC machine model is shown in Figure 2.19.

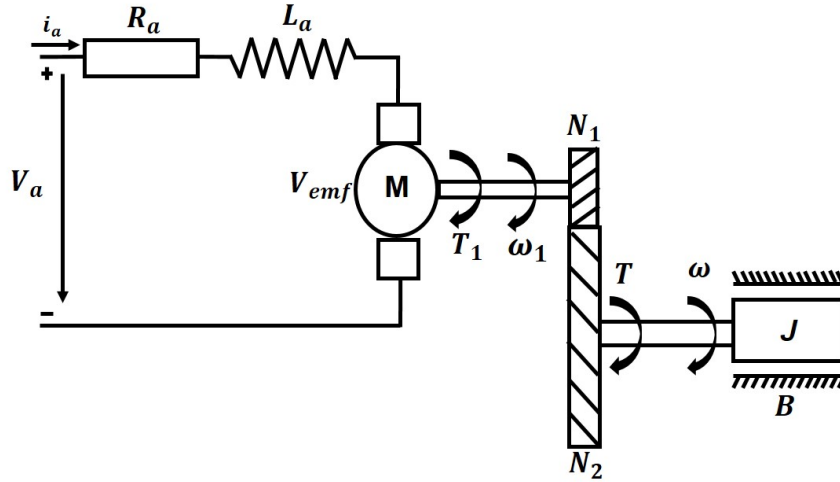


Figure 2.19. *DC electrical machine with gearbox*

An ideal gearbox is added to the basic model, where the gearbox ratio is set to $N_1/N_2 = 81/1$. In the bond graph, the gear set is represented by Transformer (TF). The bond graph of the improved DC machine is shown in Figure 2.20.

As for the sliding mode controller, a second-order time-invariant dynamic system without disturbance is demonstrated in the following:

$$\dot{x}_1 = x_2 \quad (2.5)$$

$$\dot{x}_2 = a(x) + b(x)u \quad (2.6)$$

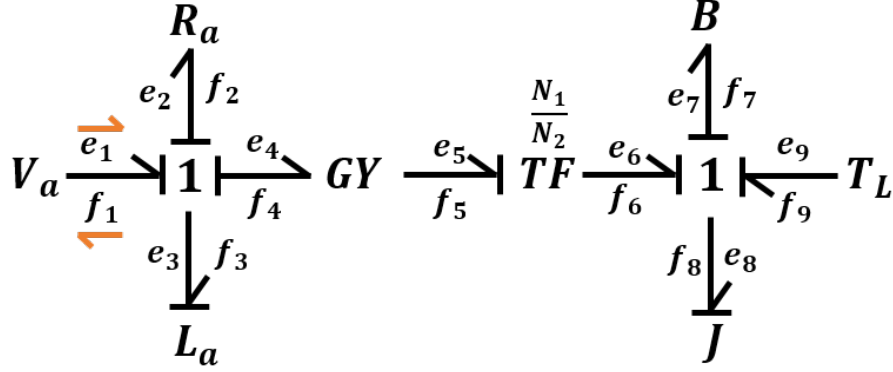


Figure 2.20. Bond Graph of DC electrical machine with gearbox

In the dynamic system 2.5 and 2.6, the sliding surface is defined in the following 2.7.

$$\sigma = x_1 + x_2 \quad (2.7)$$

The sliding mode controller control signal is described in 2.8.

$$u = e_{eq} + u_s \quad (2.8)$$

Where u_{eq} is the equivalent control to maintain the sliding mode when the system is on the sliding line. u_s is the nonlinear controller to bring the system to the sliding line surface and it is described as 2.9.

$$u_s = -\frac{k * \text{sign}(\sigma)}{b(x)} \quad (2.9)$$

Where the k is the switching control gain in the sliding mode controller, with $k > 0$. The sliding dynamic line equals zero when the system is located on the sliding surface, then $\sigma = 0$.

Substituting $u = u_{eq}$ into 2.6 under the $\dot{\sigma} = 0$.

$$u_{eq} = -\frac{x_2 + a(x)}{b(x)} \quad (2.10)$$

Then, u can be derived as 2.11 after substituting 2.9 and 2.10 into 2.8.

$$u = -\frac{k * \text{sign}(\sigma) + x_2 + a(x)}{b(x)} \quad (2.11)$$

The derivative of the sliding surface can be derived from 2.5 2.6 2.7 2.11.

$$\dot{\sigma} = -k * \text{sign}(\sigma) \quad (2.12)$$

The Lyapunov candidate function can be formed by the s dynamics 2.12:

$$V(x) = \frac{1}{2}\sigma^2 \quad (2.13)$$

The Lyapunov function is:

$$\dot{V}(x) = \sigma\dot{\sigma} \quad (2.14)$$

Substituting 2.12 into 2.14 then $\dot{V}(x)$ can be:

$$\dot{V}(x) = \sigma(-k * \text{sign}(\sigma)) \leq 0 \quad (2.15)$$

The step system can reach the sliding surface within a short period under the $k > 0$ condition. The sliding surface can be defined as in the following when c donates the sliding surface coefficient. $X_1 = \omega^* - \omega = e$, $X_2 = \dot{X}_1 = \dot{e}$. ω^* donates the reference velocity, ω is the output angular velocity. e represents the difference between the ω^* and ω .

The control signal on the sliding surface of the sliding mode control can be defined as:

$$u = k * \text{sign}(\sigma) \quad (2.16)$$

The DC machine Laplace transfer function is:

$$\frac{\omega(s)}{u(s)} = \frac{\frac{k_m}{J * L_a} * \frac{N_2}{N_1}}{s^2 + (\frac{R_a}{L_a} + \frac{B}{J})s + \frac{R_a}{L_a} * \frac{B}{J} + \frac{k_e * k_m}{J * L} * (\frac{N_2}{N_1})^2} \quad (2.17)$$

Let $\beta_1 = \frac{k_e * k_m}{J * L} * \frac{N_2}{N_1}$, $\beta_2 = \frac{R_a}{L_a} * \frac{B}{J}$, $\beta_3 = \frac{k_e * k_m}{J * L} * (\frac{N_2}{N_1})^2$, and the inverse Laplace transfer function is:

$$\ddot{\omega} + \beta_2 * \dot{\omega} + \beta_3 * \omega = u * \beta_1 \quad (2.18)$$

The position and velocity error are $X_1 = \omega$, $X_2 = \dot{X}_1$, then:

$$\dot{X}_2 = \ddot{\omega} = u * \beta_1 - \beta_2 * \dot{\omega} - \beta_3 * \omega \quad (2.19)$$

The sliding mode controller switching function and dynamic switching line are:

$$\sigma = c * e + \dot{e} = c(\omega_{ref} - \omega) + (\dot{\omega}_{ref} - \dot{\omega}) \quad (2.20)$$

$$\dot{\sigma} = c * \dot{e} + \ddot{e} = c(\dot{\omega}_{ref} - \dot{\omega}) + (\ddot{\omega}_{ref} - \ddot{\omega}) \quad (2.21)$$

The ω_{ref} donates the speed reference. and σ is the switching surface, $\sigma = 0$ when the dynamic system reaches the switching line, then $\dot{\sigma} = 0$.

$$c(\dot{\omega}_{ref} - \dot{\omega}) + \ddot{\omega}_{ref} - u * \beta_1 + \beta_2 * \dot{\omega} + \beta_3 * \omega = 0 \quad (2.22)$$

Since the derivative of the reference $\dot{\omega}_{ref} = 0$, then the equivalent equation is expressed as:

$$\beta_1 * u_{eq} = \beta_3 * \omega + (\beta_2 - c)\dot{\omega} \quad (2.23)$$

Then u_{eq} the equivalent equation of the sliding mode is shown as:

$$\beta_1 * u_{eq} = \frac{\beta_3 * \omega + (\beta_2 - c)\dot{\omega}}{\beta_1} \quad (2.24)$$

The relationship of the sliding mode controller and the DC machine plant is shown in the block diagram Figure 2.21. Nonlinearity in the SMC system is provided by the switching function $k * \text{sign}(\sigma)$. The equivalent function u_{eq} provides the maintenance of the dynamical system. As for the sliding surface, u_s is the switching function which is from the $\text{sign}(\sigma)$.

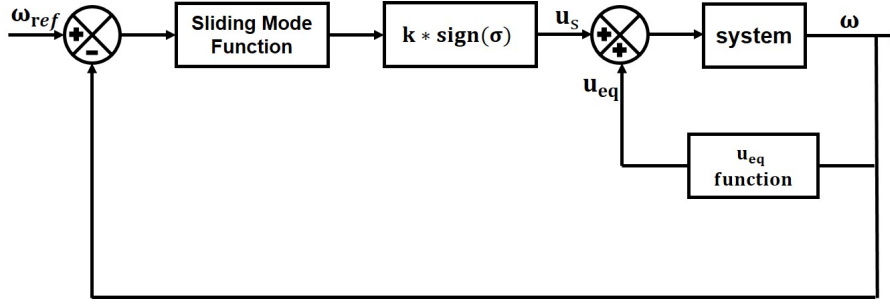


Figure 2.21. Block diagram of DC machine speed control using SMC

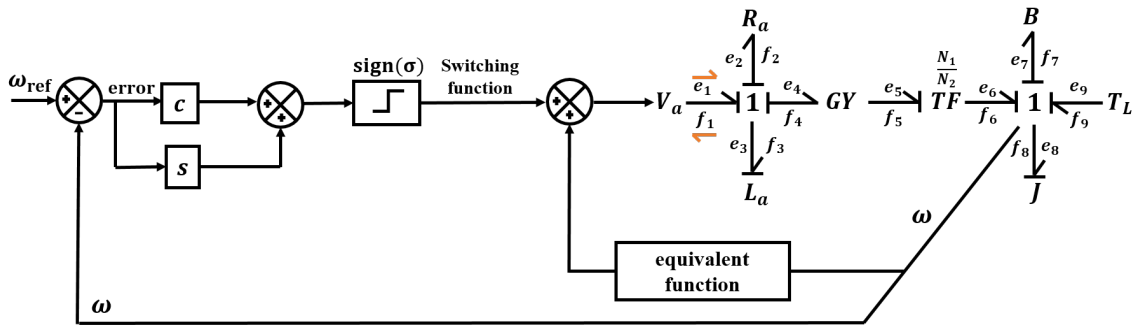


Figure 2.22. Active Bond Graph of the DC machine speed control using SMC

The active Bond Graph expresses the energy flows in the sliding mode dynamic system. The block diagram of the SMC dynamic system is derived from the inverse Laplace transfer

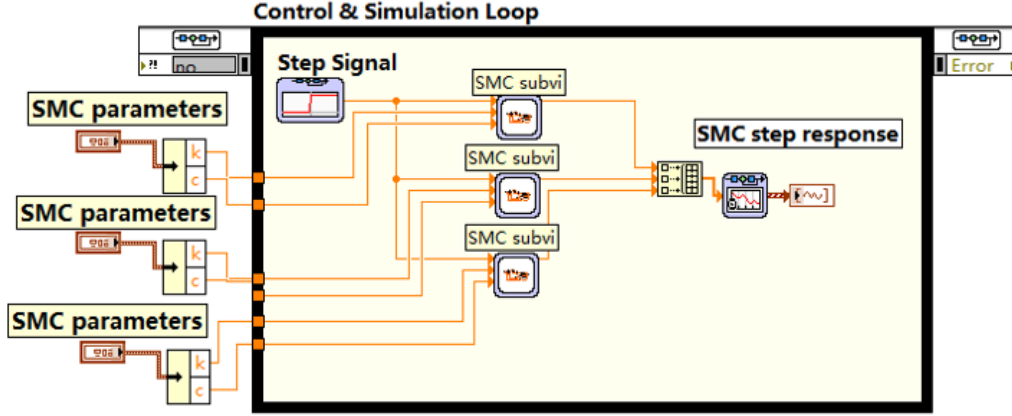


Figure 2.23. *The DC machine speed control using SMC in LabVIEW*

function. The whole process is described in Figure 2.22. The Active Bond Graph of the DC machine speed control using SMC in LabVIEW is presented in Figure 2.23.

The Active block diagram of the DC machine speed control using SMC in LabVIEW is presented in Figure 2.23.

The classic nonlinear sliding mode controller still makes it a marvelous teaching material for mechatronics engineering because of its complex abstraction but simple application. In the meantime, the active Bond Graph makes the simulation graphically and easy to understand. Where, $k = 6$.

The step response of the sliding mode controller with different parameter c is described in Figure 2.24. The figure shows that the response time decreases with the sliding surface coefficient c increases. The $e - \dot{e}$ trajectory plot is a practical tool to show the performance of the sliding mode controller. The position error is located on the horizontal coordinate and the vertical axis for the velocity error. The rate of the sliding mode convergence increases while the sliding surface coefficient c rises. The trajectory plots in Figure 2.25.

The nonlinear sliding mode controller has a robust advantage and chattering disadvantage compared with the linear PID controller. Both of these two controllers are widely used in plenty of applications. Where $k = 4, c = 8.6, k_p = 1.7, k_i = 0.1, k_d = 0.01$.

The sliding mode controller step response reaches the desired value without an overshoot, compared with the SMC controller, the PID controller normally has an overshoot

SMC step response

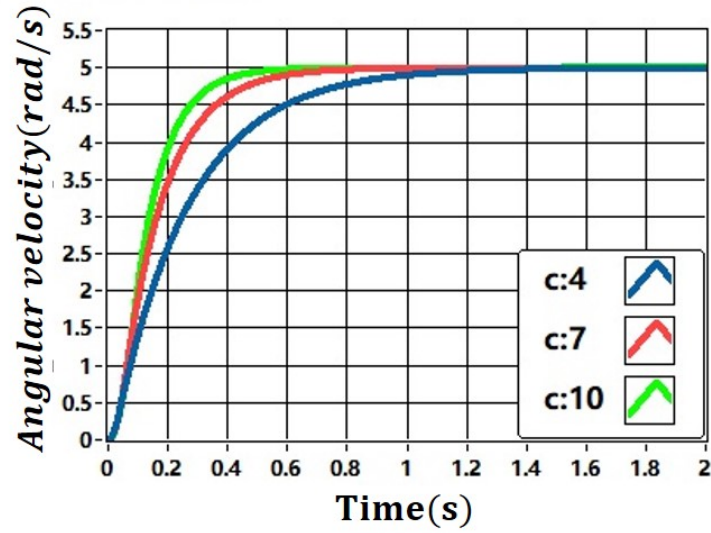


Figure 2.24. SMC step response with different c

$e - e_{dot}$

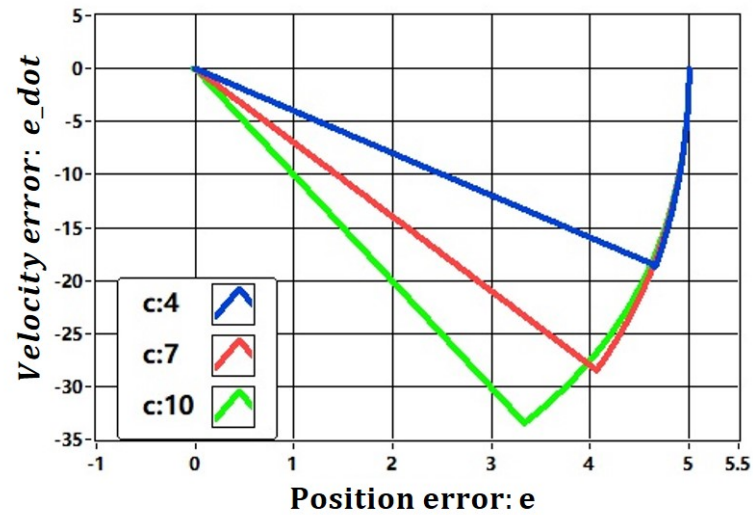
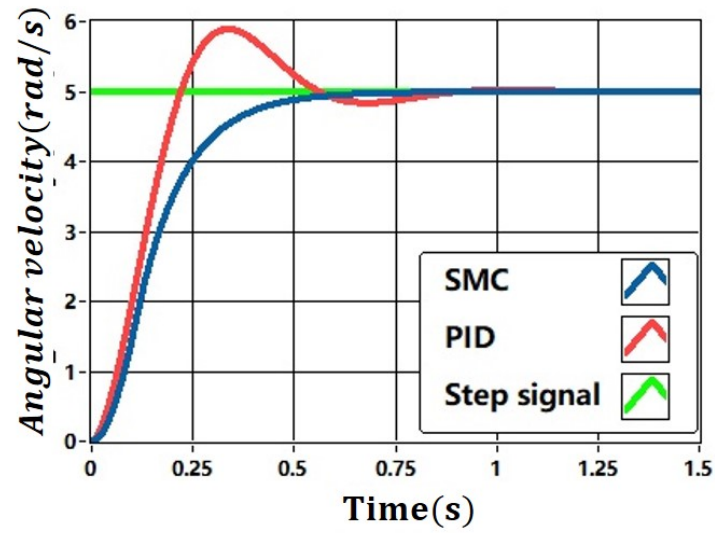


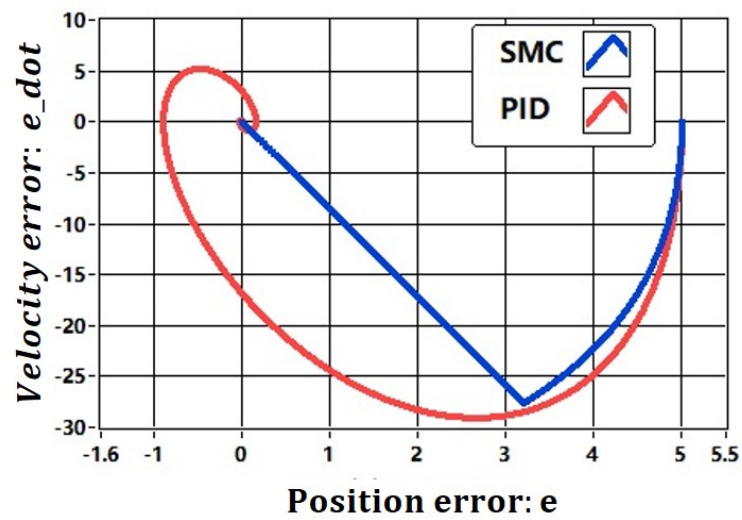
Figure 2.25. SMC e and $\dot{e}$ with vary c

Step response of PID and SMC



(a) Step Response of PID and SMC

$e - e_{dot}$



(b) e and $\dot{e}$ of the PID and SMC

Figure 2.26. Step response, e and $\dot{e}$ of the PID and SMC

in the step response in Figure 2.26(a).

Compared with the PID controller, the sliding mode controller has a faster step response 2.26(b). The reaching phase and the sliding mode phase consist of the whole nonlinear sliding mode controller. The dynamic target slides along the sliding line to the original when it reaches the sliding surface. For the position and velocity error plot, the PID controller has an overshoot after it crosses the vertical velocity axis, and the target gets to the original later on.

In this chapter, we introduced the difference between the traditional mathematical method and the Bond Graph method. Both of the methods share the purpose of achieving the same simulation results. But compared with the traditional mathematical methods such as ODEs, the graphical Bond Graph tool provides a blueprint of the whole system. The Bond Graph expresses a perspective of the vision but not the abstraction concepts. It is easy for the mechatronics engineering students to grasp the whole picture of the knowledge. Since the knowledge is separated by the blocks, then it can be introduced to the students by module. After the simulation can be created from the block diagram converted from the Bond Graph, the way of designing technology's main purpose is to guide the students to be good engineers. The study of LabVIEW can also be a core competency for students looking for a job.

2.2.6 Demonstration of Multiple Domains

There are three domains in the figure 2.27. The demonstration[53] is considered a good case study since electrical parts, mechanical parts, and hydraulic systems are connected in the schematic 2.27.

The electrical components provide voltage for the entire system, while the mechanical parts generate rotational energy for the hydraulic system. The hydraulic components offer pressure or other movements to the system.

The first step of modeling and simulation is to analyze the schematic. The next step is to convert the schematic to the Bond Graph. It is required to derive the traditional mathematical ODEs in three different fields, but the Bond Graph could express these three different fields based on the synergy of the Bond Graph characteristics. The Bond Graph

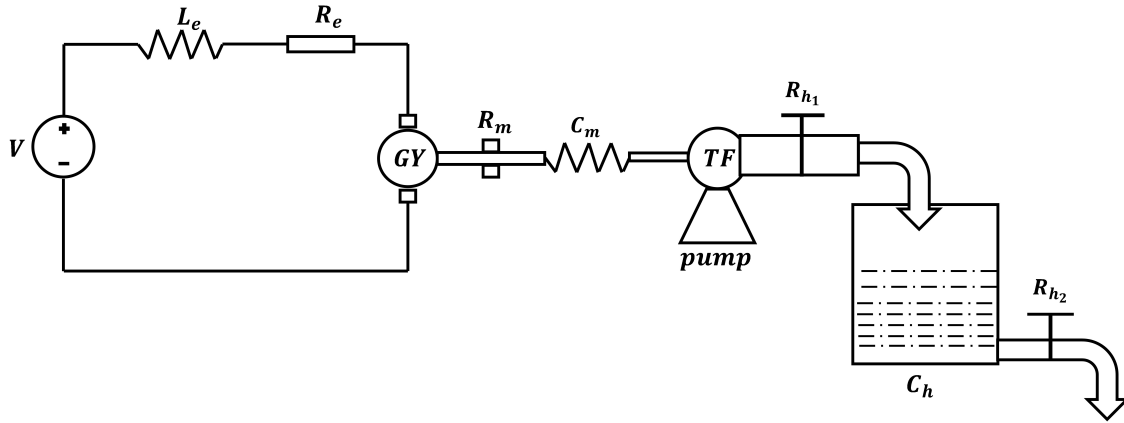


Figure 2.27. Schematic of the whole hydraulic system

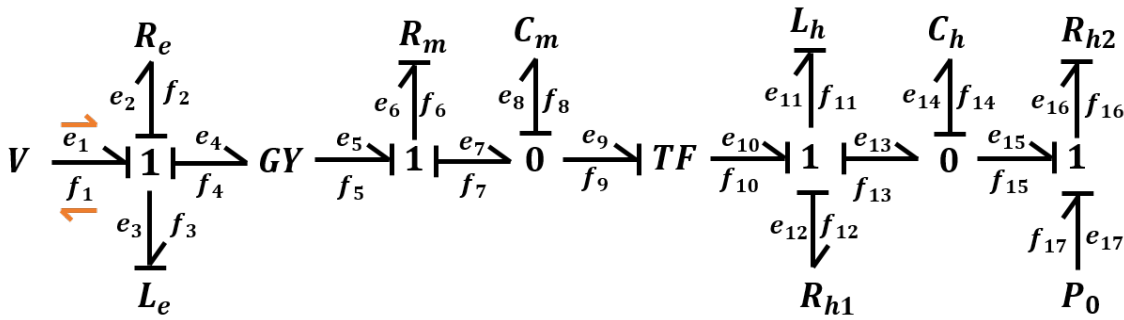


Figure 2.28. Bond Graph of hydraulic system

of the whole system is shown in Figure 2.28.

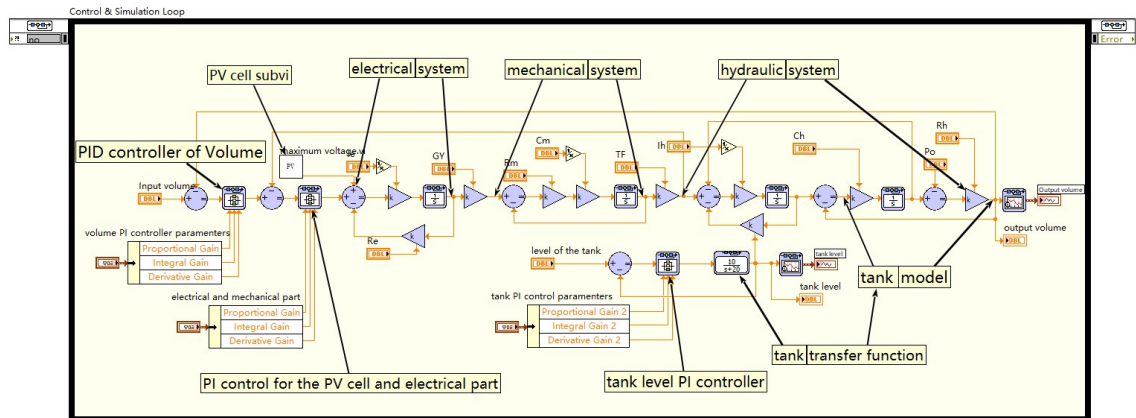


Figure 2.29. Block diagram of the whole system in LabVIEW

The last step for the simulation is to derive the block diagram from the Bond Graph.

These steps eliminate the complex calculations to have a shortcut in the modeling and simulation. The Bond Graph provides a graphical point of perspective to understand the complex mathematical OEDs as well. The last step is to have the simulation in the LabVIEW shown in Figure 2.29.

2.3 Bond Graph Representation for Linear and Nonlinear Controllers

The Bond Graph is a typical and effective representation of dynamic traditional mathematics, as well as a practical tool for control systems. The expanding requirement for control theory by the control specialists and engineers reveals the necessity of the Bond Graph in the control theory. It is essential to introduce an alternative educational method for non-specialists to understand the principles of control theory. This alternative method could offer mechatronics engineers a tool to improve their skills, ranging from mechatronics design to control theory design [113].

The DC machine Figure 2.19 with the controller is a suitable demonstration because of its electronics and mechanical domains from the perspective of mechatronics. From the control theory point of view, the magnetic field could be considered as a constant if it is an ideal DC machine. In this case, the torque, position, and velocity of the DC motor can be considered as the variables in the control design.

The PID controller is a basic linear controller, which is covered at the beginning of all controller books. The dissertation starts with a novel description of the PID controller first. After the basic controller, the sliding mode controller follows up as an advanced controller. It is widely used in the field of motion control systems because of contains the power electronics components in the real system. The switching mode transistors make the controller a typical variable structure control system. The sliding mode controller is a variable structure system with complex mathematical descriptions from a mathematical point of view and a straightforward application from a mechatronics engineering perspective. The mechatronics engineering students could program the SMC without mastering difficult technique skills. Based on the literature, the PID and SMC controller Bond Graph

representation is a novel method with no previous research.

2.3.1 Demonstration of the Bond Graph in Dynamic System

The DC machine is a demonstration utilized as teaching material in the modeling and simulation. The DC electrical motors are modeled as a fundamental actuator in Mechatronics Engineering for the undergraduate subjects. It is a better solution for electrical machine modeling to simplify as a DC motor. In reality, DC electrical machines are commonly demonstrated as actuation elements in industrial applications. The DC electrical machines are simple enough to analyze their modeling, which makes them an ideal model for educational purposes.

On the left side of the electrical circuit, there is a series connection with a voltage resource, an inductor, and a resistor. A gearbox and winding with the moments of inertia consist of the mechanical side of the DC machine. An “ideal motor” connects both electrical and mechanical parts shown in Figure 2.19. This ideal motor in Figure 2.19 consists of a resistance R_a , an inductor L_a , and the back electromotive force V_{emf} .

An ideal gearbox ratio is set to $N_1/N_2 = 81/1$. And the parameters of the gearbox is shown in Table 2.5 for convenient simulation. Where the torque and angular velocity relationship are: $T_1/T = N_1/N_2$, and $\omega_1 * N_1 = \omega * N_2$. The mathematical representation of the DC machine is shown in 2.25 and 2.26.

$$L \frac{d i_a}{d t} = V_a - R * i_a - k_e * \omega * \frac{N_2}{N_1} \quad (2.25)$$

$$J \frac{d \omega}{d t} = k_m * i_a * \frac{N_2}{N_1} - B * \omega - T_L \quad (2.26)$$

On the left side, a resistor $R_a(\Omega)$, an inductor $L_a(H)$, and the back electromotive force V_{emf} consists of the electrical part of the rotor; $V_{emf} = k_e * \omega$; $V_a(V)$ donates the armature voltage, $i_a(A)$ represents the armature current of the electrical circuit. On the right side of the rotor, $T_1(Nm)$ is the electromechanical torque generated by the motor, $T(Nm)$ is the torque transform by the gearbox, and $T_L(Nm)$ is the torque load. “ ω ”(rad/s) donates the speed of the motor, $\omega_1(rad/s)$ is the speed of the rotor, $J(gcm^2)$ and $B(Nms/rad)$ represents the rotor inertia and the viscous friction of the DC

Table 2.5. *PARAMETERS of Gear Drive(110396)*

Gear Drive(110396)	
Max efficiency	80%
Number of stages	3
Reduction	81:1
Reduction Absolute	2197/27
Max continuous Torgue at Gear output	1.8Nm
Intermittently Permissible Torque at Gear Output	3.0Nm

motor electrical part. $k_e(Vms/rad)$ and $k_m(mNm/A)$ represent the Gyrator's back EMF constant and motor constant respectively [8].

The Bond Graph of the DC motor is shown in Figure 2.20. There are two parts of the bond graph. 1-junction can represent energy flows of the electrical and mechanical parts of the system respectively. The gyrator's function is to connect two parts since the rotor of the DC machine can convert from one form of energy to another form of energy. The energy effort and the energy flow can be converted to each other by the gyrator. TF represents the gearbox in the schematic since the gearbox shares the same form of energy on both sides. The numbers above the bond make the energies and flow more visualized and it can be analyzed easily.

The next step of the simulation process is to convert the Bond Graph to the block diagram which is shown in Figure 2.30. It can illustrate the directions of energies and flows that complex mathematical calculations can not detect. Compared with the traditional learning method such as ordinary differential equations, the Bond Graph method is much more acceptable for the students based on their responses.

The components donate the relation is shown in the flowing: the first 1-junction represents the common flow energy; the current is the common flow in the electrical circuit.

The effort energy should do the calculation because of the 1-junction. $e_1 = e_2 + e_3 + e_4$, based on the direction of the Bonds, the output of the first junction is e_3 . Then the equation is $e_3 = e_1 - e_2 - e_4$. The second 1-junction has the same logic, $e_8 = e_6 - e_7 - e_9$. TF is the gearbox and the k_e and k_m is the GY parameters.

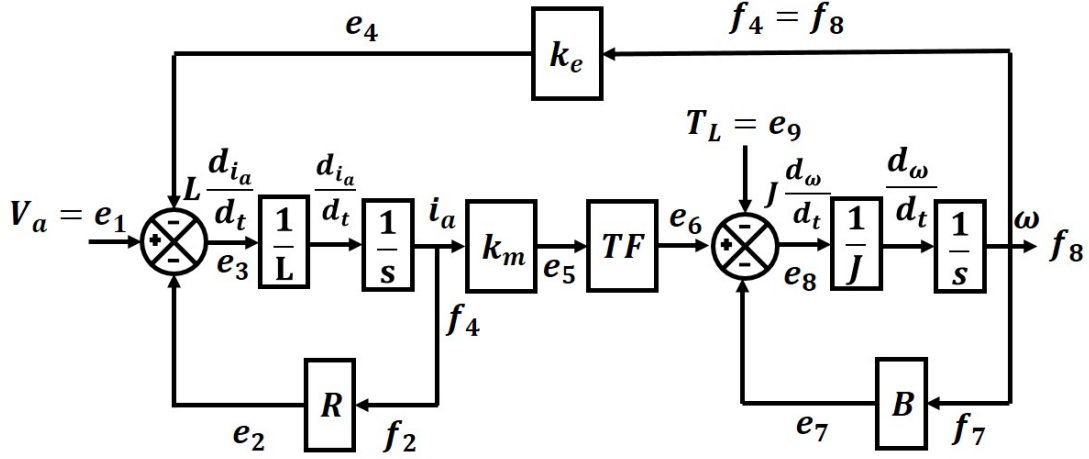


Figure 2.30. Block diagram of DC machine

These are the two methods of deriving the block diagram of the dynamic model. The mathematical ordinary differential equations (ODE) and the Bond Graph. On the other hand, the mathematical method is the theoretical or numerical method. The bond Graph is the analytical method during the research, which provides researchers with a novel graphical tool to derive the block diagram from the schematics.

2.3.2 Bond Graph Representation of Operational Amplifier

Before discussing the PID controller, the Bond Graph representation of the operational amplifier should be introduced first.

Operational amplifiers (op-amps) are commonly utilized in a variety of electronic applications. OP-amps can be considered as the core of signal applications, such as amplifiers, integrators, and differentiators. Different combinations of the op-amps can achieve multiple functions of the applications with the resistors, inductors, and conductors connected. The op-amps are one of the integrated circuits (IC) with a high input resistance and a low output resistance. The op-amps can provide extra functions based on the different

conditions of the different components.

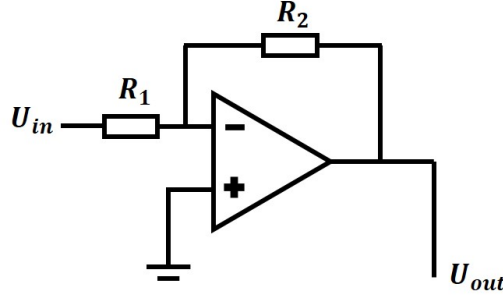


Figure 2.31. *simple operational amplifier*[113]

The operation amplifier is a good teaching material in the mechatronics engineering subjects. As we know, the operational amplifier is a functional circuit, which can represent the PID controller in a circuit. The operational amplifier is shown in Figure 2.31 and 2.32.

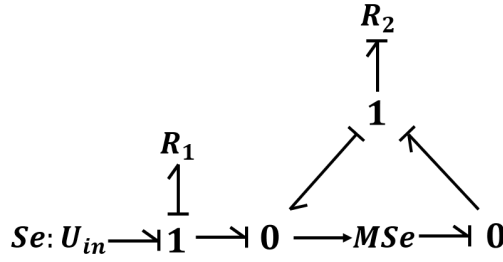
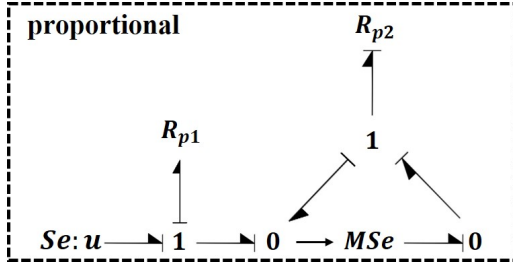


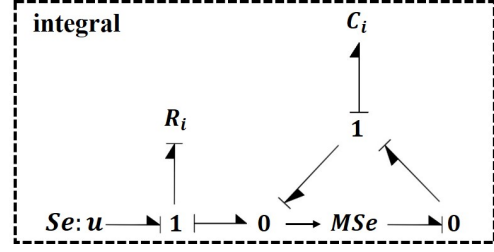
Figure 2.32. *Bond Graph of operational amplifier*[113]

In realistic applications, an operational amplifier(op-amp) is used with the resistors, and capacitors connected as a feedback circuit. One of the simple demonstrations of the inverting operational amplifier is shown in Figure 2.31, It is an operational amplifier circuit where the output voltage changes inversely with the input voltage. It represents the ratio of the output voltage to the input signal. The Bond Graph representation of the inverting operational amplifier is illustrated in the figure 2.32 [1].

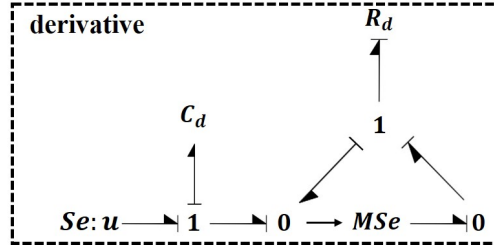
Besides the inverting op-amps, there are other types of op-amps called summing op-amps, integral op-amps, and derivate op-amps. These op-amps have the function of proportional, integration, and derivation. All these op-amps could be represented using the basic Bond Graph. The Figure 2.33(a) is a classical inverting op-amp, which can realize the function of the proportional by changing the ratio of the parameters R_{p1} and R_{p2} .



(a) *simple inverting operational amplifier*



(b) *Bond Graph of integral operational amplifier*



(c) *Bond Graph of derivative operational amplifier*

Figure 2.33. *proportional, integral, derivative Operational Amplifier and its Bond Graph*

Based on the integral op-amps, by replacing the resistor on the feedback circuit with a capacitor, the operational amplifier can make the input and output have an integral relationship Figure 2.33(b). The same logic to the derivative op-amps, by changing the resistor on the input circuit with a capacitor, the inverting op-amps can obtain the function of the derivative Figure 2.33(c).

After introducing the Bond Graph representation of the Proportional, integral, and derivative controllers respectively, these three types of controllers need to be summed to fulfill the PID controller. The summing function can use the op-amps as well, which is shown in Figure 2.34. The output of the Proportional, integral, and derivative controllers are the three inputs of the summing OP-AMPS, and the output of the summing OP-AMPS is the negative control signal, in this case, an inverter is needed to reverse the signal to the positive one. The inverter of the OP-AMPS is shown in Figure 2.37.

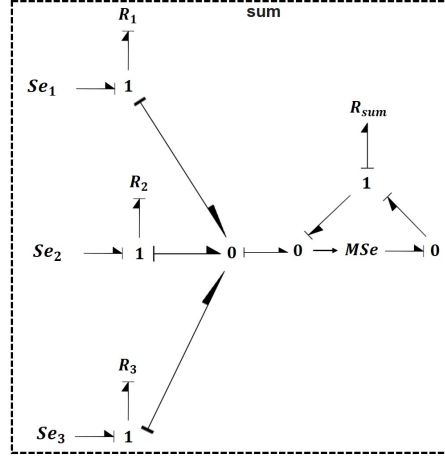


Figure 2.34. Bond Graph of sum OP-AMPS

2.3.3 Bond Graph Representation of PID controller

We propose two compared methods in the mechatronics engineering teaching strategies. The Bond Graph on the left as a novel teaching method could provide students with a clear blueprint for the simulation process, another method on the right is the traditional method such as mathematical ODEs, the mathematical method could illustrate the theory of the simulation. Both of the methods serve the same purpose, which is to convert the schematic of the real physical system to the dynamic simulation results. The Bond Graph could convert the schematic to the block diagram directly compared with the traditional method. And the bonds in the Bond Graph depict the energy flows in the dynamic system.

The Bond Graph provides a clear relationship of the whole system from a graphical perspective in mechatronics engineering. The multiple domain combination using the Bond Graph solution also presents the synergy in the mechatronics engineering subjects.

This section presents new teaching methods for the students, in the meantime, we also provide teaching strategies. The teaching strategy is to make the knowledge modular, which could train students to think by themselves when they face a new assignment by applying the knowledge modularly. The researchers such as the mechatronics engineering students could integrate knowledge modularly presented in Figure 2.36.

In control theory, linear control is one of the fundamental control strategies, and in the meantime, the PID controller is a classical controller for the DC machine speed control

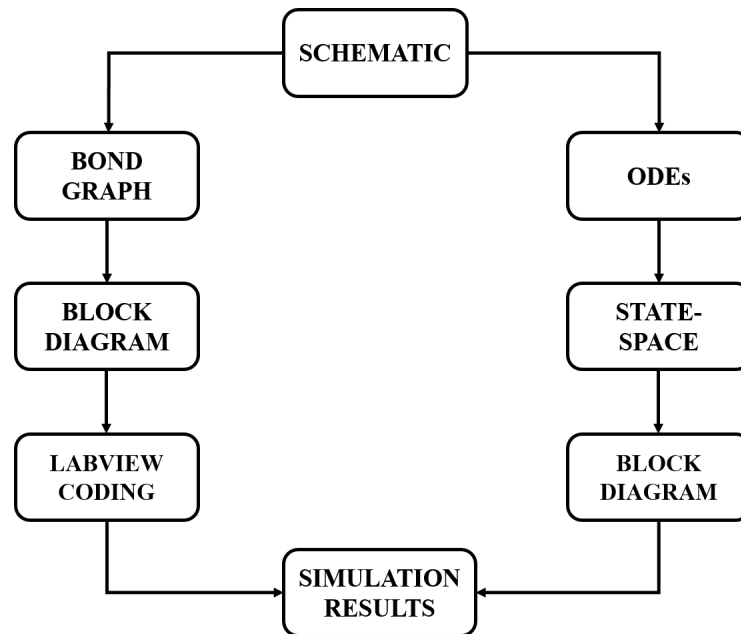


Figure 2.35. Comparison two methods [8]

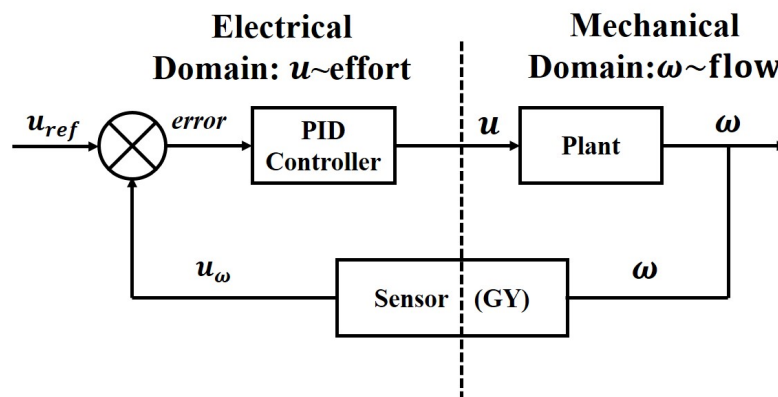


Figure 2.36. Modular the block diagram of the control system [8]

in the linear control domain.

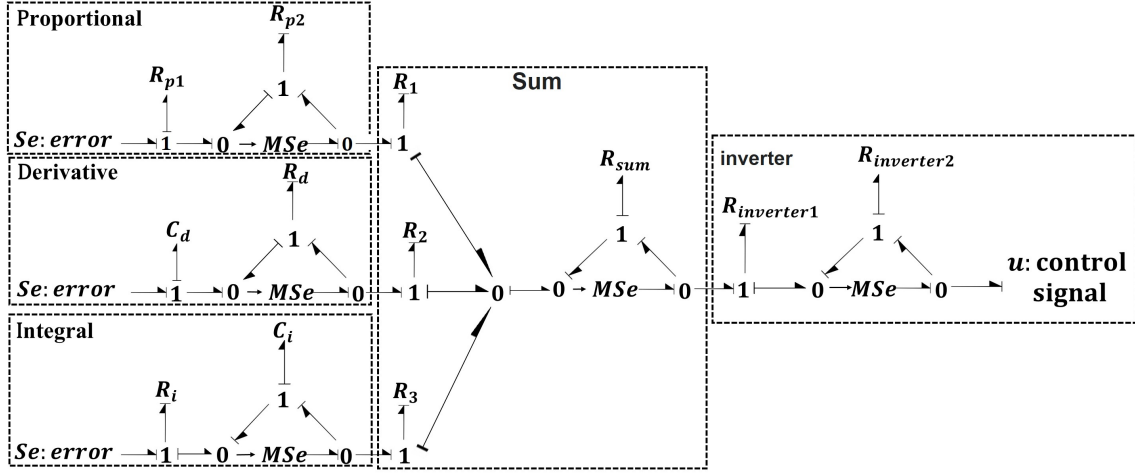


Figure 2.37. PID representation using Bond Graph

A PID controller can be represented using operational amplifiers in a bond graph format. There are inverter, differential, and integral operational amplifiers in the PID controller Bond Graph. The PID controller Bond Graph is shown in Figure 2.37.

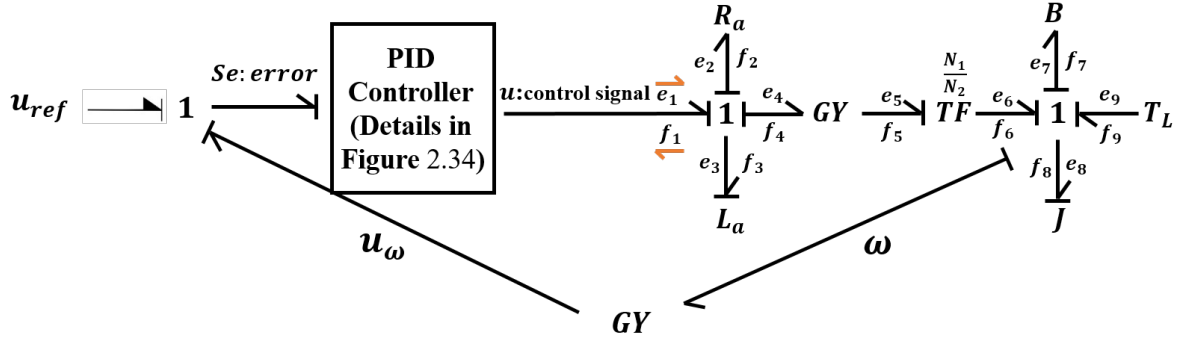


Figure 2.38. Active Bond Graph of PID controller

The input of the PID controller is the $Se : u$, which represents the difference between the reference input and the measurement output. u is the control signal of the DC motor plant. The GY symbol on the feedback bond graph is a tachogenerator, which can convert the flow energy into effort energy. The active Bond Graph of the PID controller is shown in Figure 2.38.

Figure 2.37 and Figure 2.38 are a little bit complex for the electrical and control

engineering students, but from a graphical language point of view, it is clearly pleasant for the mechatronics engineering students during the simulation study.

After the theoretical part of the modeling and simulation, the result should be added and analyzed as in the following. The Figure could present the step response of the DC motor speed control using different k_i . The step response of the PID with varying k_i is shown in Figure 2.39. With different parameter settings, there is a slight difference in the performance, such as the step response overshoot increase with the increase of the k_i . Other parameters are $k_p = 1$, $k_d = 0.01$. The Bond Graph and the traditional method share the same result of the schematics. This plot presents the characteristics of the step response with different simulation parameters.

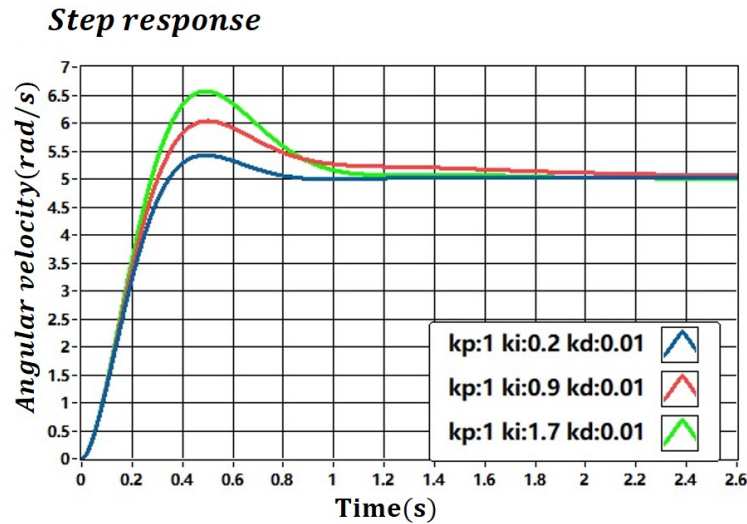


Figure 2.39. DC motor speed control using PID controller with different k_i

The next figure is the trajectory of the PID controller performance, the position and velocity trajectory could help students understand the convergent performance, e and $\dot{e}$ illustrate the position and velocity error respectively in Figure 2.40.

The trajectories could converge to the origin in a finite time, and the position error increases with the increase of the parameter k_i . These two methods' processes are different, the simulation result of the step response and the trajectory are the same. The Bond Graph could be considered as an alternative method to the mathematical calculation during the modeling and simulation in mechatronics engineering.

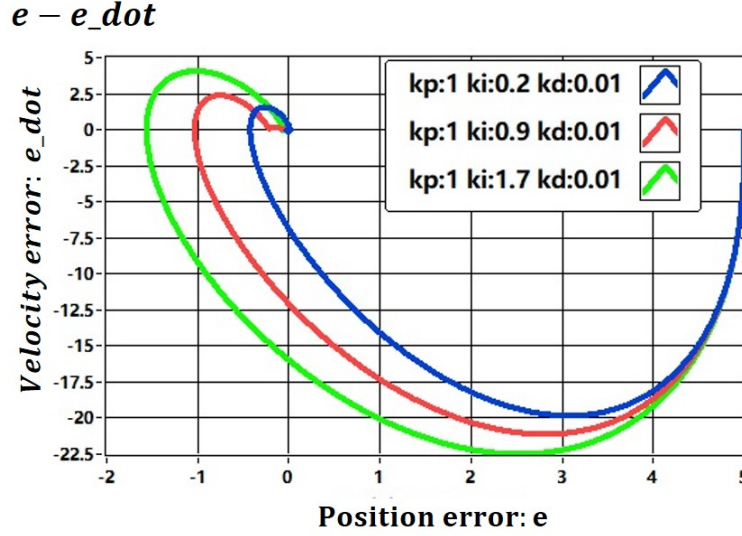


Figure 2.40. PID controller e and $\dot{e}$ with different k_i

2.3.4 Bond Graph representation of General Sliding Mode

After introducing the PID controller in the linear control theory, a nonlinear controller could be another classical teaching material in the mechatronics engineering subjects. With the iteration of the knowledge, the acceptance of nonlinear control for mechatronics engineering students has increased. Since the theory of the sliding mode control is complex enough and simple enough in the implementation for mechatronics engineering students, then nonlinear control should be introduced in the undergraduate teaching materials. One of the most efficient nonlinear controllers is the sliding mode controller, which is applied to undergraduate teaching materials. The sliding mode controller is typical of the nonlinear controller in the dynamic system. In this section, we present a normal sliding mode controller for position and speed tracking. Then an adapt robust sliding mode controller method is introduced using the general model and real DC electrical machine parameters respectively.

Since the modular becomes a teaching strategy of the teaching methods, then it will be applied on the sliding mode controller as well. The knowledge is divided into parts and combined with the block diagram in Figure 2.41. At the first beginning, the ideal sine position signal is set as the input of the whole system, the output is the $\theta_d(t)$. The second

block is the sliding mode control, this modular generates the control signal $u(t)$. The last module is the plant model.

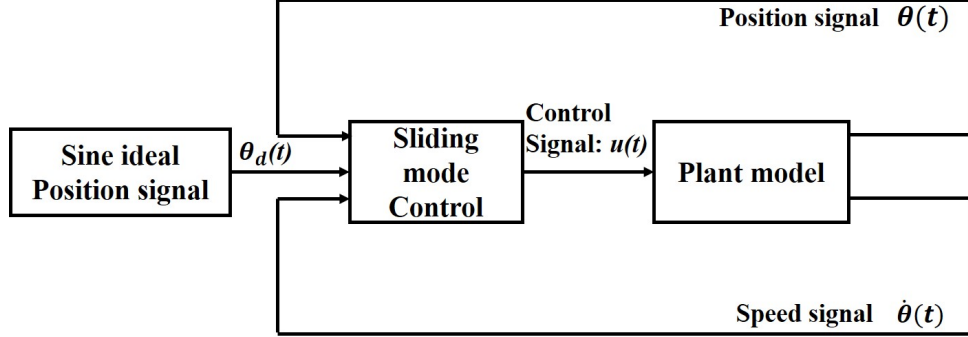


Figure 2.41. *a general sliding mode control*

The equations of DC motor (2.25) and (2.26) can be written in the following simple second-order form:

$$J\ddot{\theta}(t) = u(t) + d(t) \quad (2.27)$$

Where J is the moment of inertia; $u(t)$ is the control input i.e. the voltage of the motor; $d(t)$ is the disturbance, which must be a limited function. It can include external functions like the load torque and the internal first-order terms because of R and B . This means that in this case, we do not need to know all the parameters of the motor, only J is known exactly. We would like to emphasize that during the design of the controller, the inductance of the rotor circuit (the electric time constant) is ignored. We consider it as unmodelled dynamics, which is covered by the controller. It is quite common in the engineering field that we start with a simple model. The goal is to use the simplest model, which provides satisfactory results.

The sliding surface is designed as follows:

$$s(t) = ce(t) + \dot{e}(t) \quad (2.28)$$

Where c is satisfied Hurwitz condition, $c > 0$. Tracking error and tracking error derivative are shown as follows:

$$e(t) = \theta(t) - \theta_d(t) \quad \text{and} \quad \dot{e}(t) = \dot{\theta}(t) - \dot{\theta}_d(t) \quad (2.29)$$

Where $\theta_d(t)$ is the ideal angle signal.

Our goal is that the $s(t) \rightarrow 0$. The sliding mode occurs if $s(t) = 0$. In sliding mode, the error tends to zero exponentially. The solution is quite easy from the mathematical point of view, we have to find a proper Lyapunov and use the Lyapunov condition. We will show this method in the next subsection but in our case, it can be explained by very elementary mathematical tools as well. If $s(t) > 0$ then $\dot{s}(t)$ must be decreased i.e $\dot{s}(t) < 0$. If $s(t) < 0$ then $\dot{s}(t)$ must be increased i.e $\dot{s}(t) > 0$. We can change the control signal only. That is why we use a term in the control signal which is changing according to the sign of $s(t)$. The easiest solution is the signum function. Finally, they can express the control signal $u(t)$. We can ignore all unknown terms of it and we assume that k is big enough to determine the sign of $\dot{s}(t)$. Since the operation area of a real motor is limited the $e(t)$ is limited as well.

A very simple sliding mode control law can be designed in a certain domain $e(t)$.

$$u(t) = k * \text{sign}(s) \quad (2.30)$$

The selection of the k should satisfy two contradictory conditions. k can not be too small to compensate for the disturbance, and not too big in order to avoid the chattering phenomenon problems. In this case, it is called equivalent control signal $u_e(t)$, which could keep the system in sliding mode ideally.

$$u(t) = u_e(t) + k * \text{sign}(s) \quad (2.31)$$

The sign function should compensate for the calculation error of the system. The $s(t) = 0$, $\dot{s}(t) = 0$ when the system is located in the sliding mode.

$$\begin{aligned} \dot{s}(t) &= c\dot{e}(t) + \ddot{e}(t) \\ &= c\dot{e}(t) + \ddot{\theta}(t) - \ddot{\theta}_d(t) \\ &= c\dot{e}(t) - \ddot{\theta}_d(t) + \frac{u(t) + d(t)}{J} \end{aligned} \quad (2.32)$$

In the simulation, the $d(t)$ is unknown to be substituted by the signum function and the control signal $u(t)$ is designed as:

$$u(t) = J * [-c * de + \ddot{\theta}_d - k * \text{sign}(s)] \quad (2.33)$$

Based on the equation 2.33, the k should be smaller enough to reduce the chattering of the sliding mode simulation system. The moment of inertia $J = 10$, $\theta_d(t) = \sin(t)$. The position and speed initial conditions are set to 0.3 and 1.0 respectively. The disturbance $d(t)$ is set to $0.5 * \dot{\theta}(t) + 1.5 * \text{sign}(\dot{\theta}(t))$, $c = 0.5$, $k = 0.5$. Figure 2.42 shows the position and speed tracking simulation result.

The position and speed tracking performance is shown in Figure 2.42. The plots spread some conclusions in the following, the initial condition of the position affects the tracking performance in the general sliding mode controller. The speed-tracking plot does not have an ideal performance even if the ideal signal is the same as the initial speed input. An adaptive robust sliding mode controller is proposed to achieve a better performance in the tracking error problem in the following.

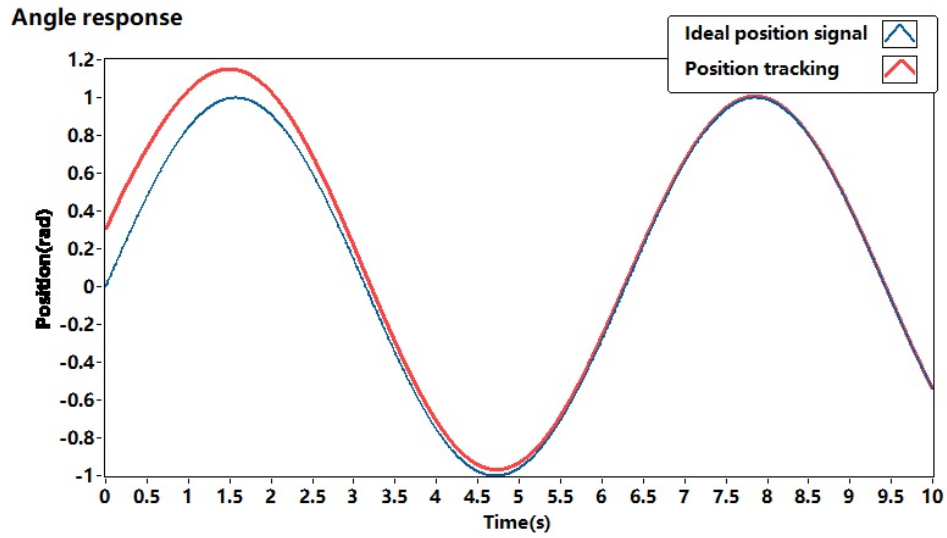
2.3.5 Bond Graph representation of Adaptive Robust Sliding Mode

Adaptive control is a controller method that can adapt its characteristics to the changes in the dynamics systems of the target and disturbances. Robust control is a dynamic system that adapts certain performance characteristics within certain parameter disturbances. The speed and position tracking plot can perform well by applying the adaptive robust mode control[114].

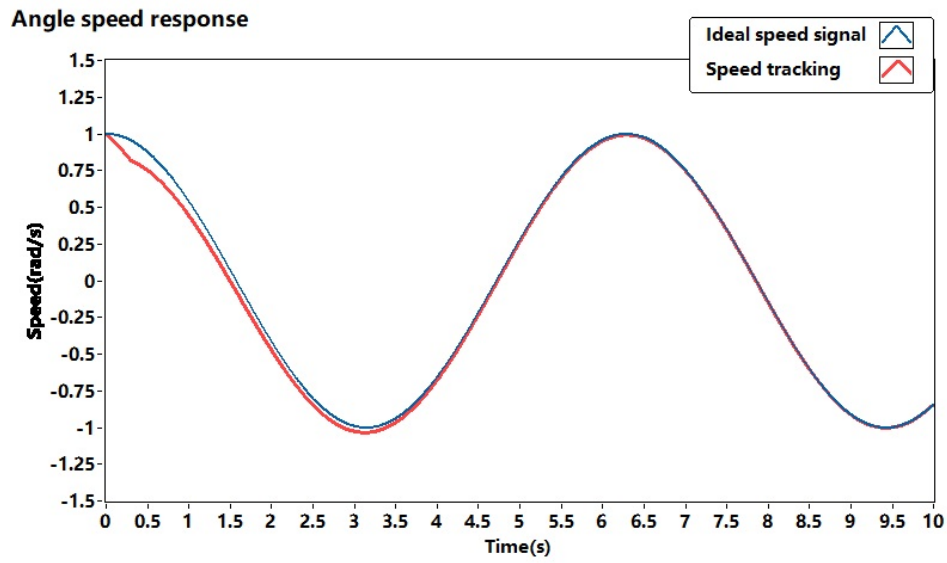
It is emphasized that J is a known value. The parameter uncertainty is also allowed because of the inertia. The parameter uncertainty is limited as the disturbance signal d . In this chapter, Based on the didactic innovation, a method is presented where the uncertainty of the J parameter is not considered part of d but it is calculated separately in such a way that the sliding mode control is combined with the estimation of a J parameter. Parameter estimation itself is part of the curriculum.

The real and estimated inertias are J and $\hat{J}$. The estimation error:

$$\tilde{J} = \hat{J} - J \quad (2.34)$$



(a) *simple Sliding mode position tracking*



(b) *simple Sliding mode speed tracking*

Figure 2.42. Simple sliding mode position and speed tracking

Our goal of $s(t) \rightarrow 0$ is extended by an additional goal $\tilde{J}(t) \rightarrow 0$

The Lyapunov function consists of two terms one for $s(t)$ and one for $\tilde{J}(t)$.

$$V = \frac{1}{2}Js^2 + \frac{1}{2\gamma}\tilde{J}^2 \quad (2.35)$$

Where $\gamma > 0$, and $V(t) \geq 0$. When $s(t) = 0$ and $\tilde{J}(t) = 0$, then $V(t) = 0$. If $V(t) > 0$, then $\dot{V}(t)$ must be smaller than 0.

$$\dot{V} = Js\dot{s} + \frac{1}{\gamma}\tilde{J}\dot{\tilde{J}} = s(J\ddot{\theta} - J\ddot{\theta}_d + Jc\dot{e}) + \frac{1}{\gamma}\tilde{J}\dot{\tilde{J}} \quad (2.36)$$

$$J\dot{s} = J(\ddot{\theta} - \ddot{\theta}_d + c\dot{e}) \quad (2.37)$$

Substituting (2.27) and (2.37) into the equation (2.36).

$$\dot{V} = s(u + d - J(\ddot{\theta}_d - c\dot{e})) + \frac{1}{\gamma}\tilde{J}\dot{\tilde{J}} \quad (2.38)$$

The equivalent control signal can be derived from the first term of $\dot{V}$. The J is the inertia, and $J > 0$. J does not change the sign of the condition as a multiplier. It can be substituted by its estimation because of its unknown characteristics. $-k_s s$ and $k * \text{sign}(s)$ are added to the equivalent control signal since in addition to suppressing the disturbance, parameter adaptation must also be ensured. $-k_s s$ is dominant if s is big; $k * \text{sign}(s)$ is dominant if s is small. To make sure the convergence of the sliding mode controller, the control signal can be designed as:

$$u = \hat{J}(\ddot{\theta}_d - c\dot{e}) - k_s s - k * \text{sign}(s) \quad (2.39)$$

Where, $k_s > 0, k > 0$. And then substituting (2.39) into the (2.38):

$$\dot{V} = s(\hat{J}(\ddot{\theta}_d - c\dot{e}) - k_s s - k * \text{sign}(s) + d - J(\ddot{\theta}_d - c\dot{e})) + \frac{1}{\gamma}\tilde{J}\dot{\tilde{J}} \quad (2.40)$$

Equation (2.40) can be derived as:

$$\dot{V} = -k_s s^2 - k|s| + d * s + \tilde{J}(s(\ddot{\theta}_d - c\dot{e}) + \frac{1}{\gamma}\dot{\tilde{J}}) \quad (2.41)$$

Then adaptive law can be set as:

$$\dot{\tilde{J}} = -\gamma s(\ddot{\theta}_d - c\dot{e}) \quad (2.42)$$

When $s = 0, V = 0$. Where $V = -k_s s^2 - k|s| + \frac{1}{2} s^2 - k_s s^2 \leq 0$. When $V \equiv 0, s \equiv 0$. When $t \rightarrow \infty, s \rightarrow 0$, The convergence of the system depends on the k_s .

In order to prevent the control input signal $u(t)$ from being too large due to too large $\hat{J}$, it is necessary to design the adaptive law so that the change of the $\hat{J}$ is within the range of $[J_{min}, J_{max}]$. A mapping adaptive algorithm is shown as:

When $\hat{J}$ exceeds the maximum value, if there is a tendency to continue to increase, $\dot{\hat{J}} > 0$, then the value of $\hat{J}$ remains unchanged, then $\dot{\hat{J}} = 0$; when $\hat{J}$ exceeds the minimum value, if there is a tendency to continue to decrease, $\dot{\hat{J}} < 0$, then the value of $\hat{J}$ remains unchanged, $\dot{\hat{J}} = 0$.

$$\dot{\hat{J}} = \begin{cases} 0 & \text{if } \hat{J} \geq J_{max} \text{ and } -\gamma s(\ddot{\theta}_d - c\dot{e}) > 0 \\ 0 & \text{if } \hat{J} \leq J_{min} \text{ and } -\gamma s(\ddot{\theta}_d - c\dot{e}) < 0 \\ -\gamma s(\ddot{\theta}_d) - c\dot{e} & \text{else} \end{cases} \quad (2.43)$$

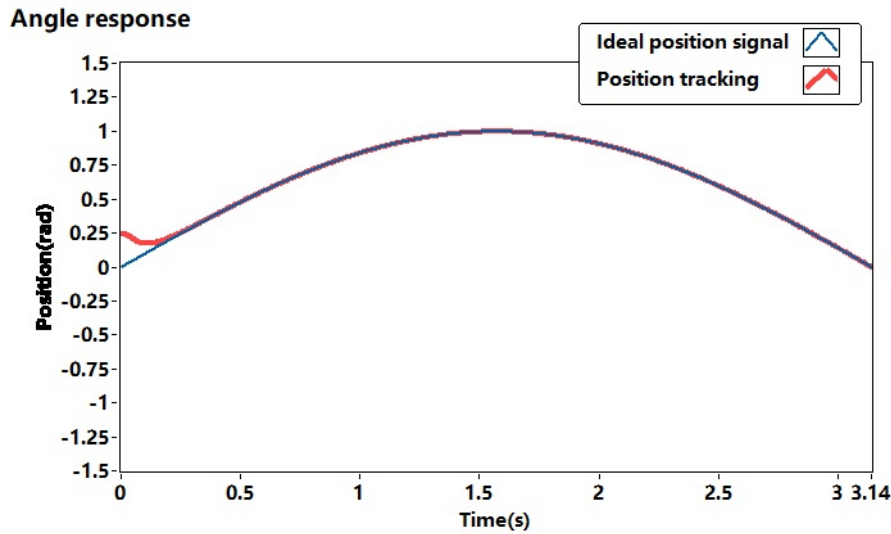


Figure 2.43. Position tracking of adaptive sliding mode controller

The position and speed tracing plot is shown in Figure 2.43 and 2.44. The initial values' conditions of the speed and position are 0 and 0.25 respectively. $J = 1$ and the target position signal is set to $\sin t$. $J_{max} = 1.5$, $J_{min} = 0.5$, $c = 15$, $k_s = 15$, $\gamma = 200$, and $k = 6.01$. $d(t) = 0.5\dot{\theta} + 1.5\text{sign}(\dot{\theta})$. The control signal u is added by adaptive part

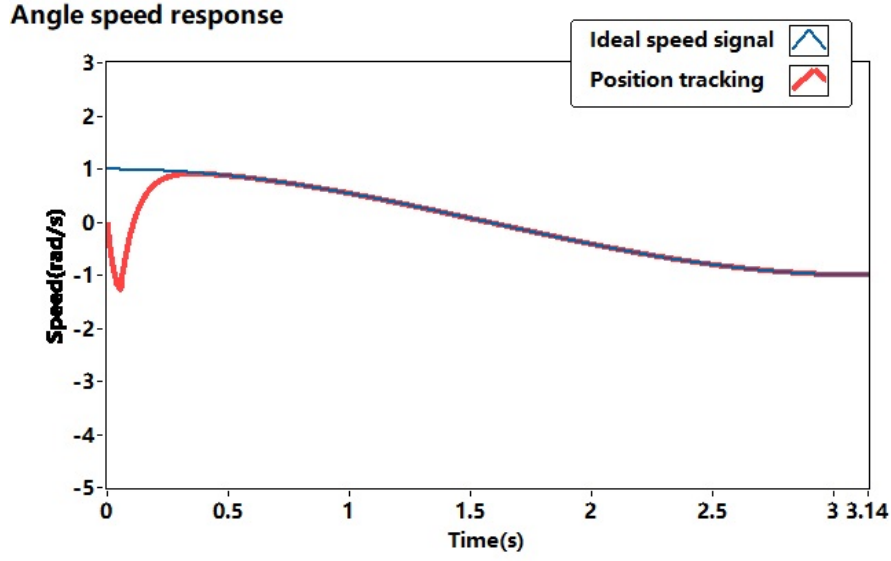


Figure 2.44. Speed tracking of adaptive sliding mode controller

u_a , sliding mode equivalent u_{s1} , and sliding control unit u_{s2} as $u = u_a + u_{s1} + u_{s2}$, where $u_a = \hat{J}(\ddot{\theta}_d - c\dot{e})$; $u_{s1} = -k_s * s$; and $u_{s2} = -k * \text{sign}(s)$. The control signals u can be limited by the adaptive law shown in Figure 2.45.

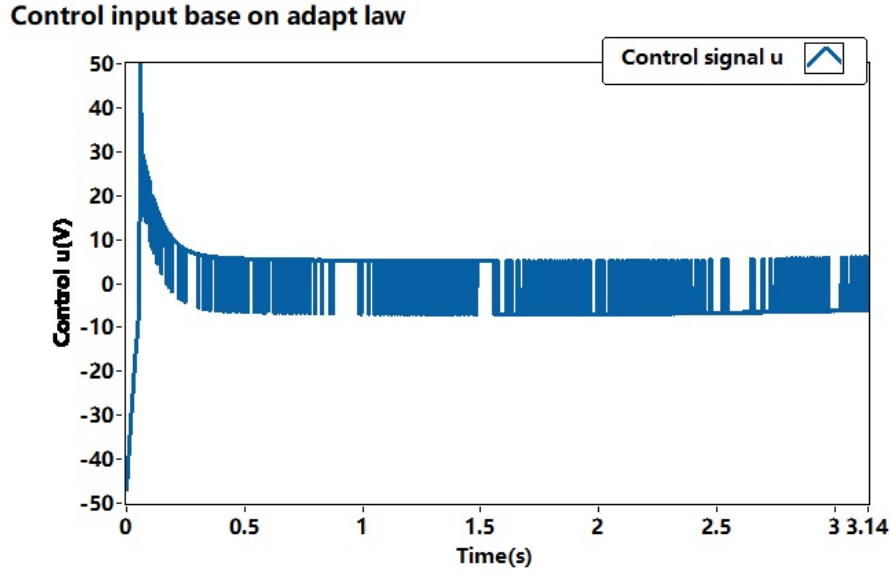


Figure 2.45. Adaptive sliding mode control signal

One of the main contributions of the dissertation is to introduce the way to represent sliding mode by using the Bond Graph method. Compared with the mathematical equa-

tions, the Bond Graph method above presents all the energy flow of the adaptive robust sliding mode control. The elements R and I are the type of energy in the bond graph. MTF is the modulated transformation, it can be considered as a gain in the bond graph. $x_1 : \theta$ and $x_2 : \dot{\theta}$ are the position and speed respectively in the control loop. $x_d : \theta_d$ is the ideal position input.

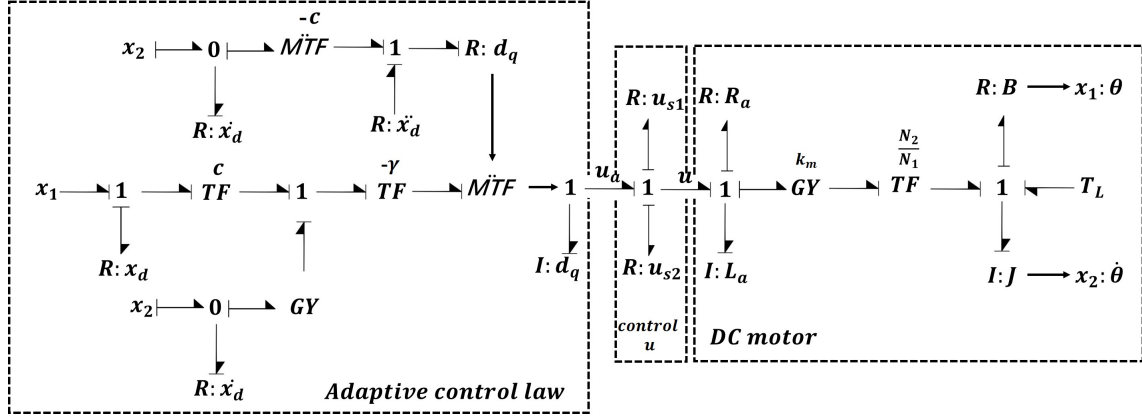


Figure 2.46. Bond Graph of adaptive control law

The block diagram of the adaptive control in LabVIEW is shown in Figure 2.47.

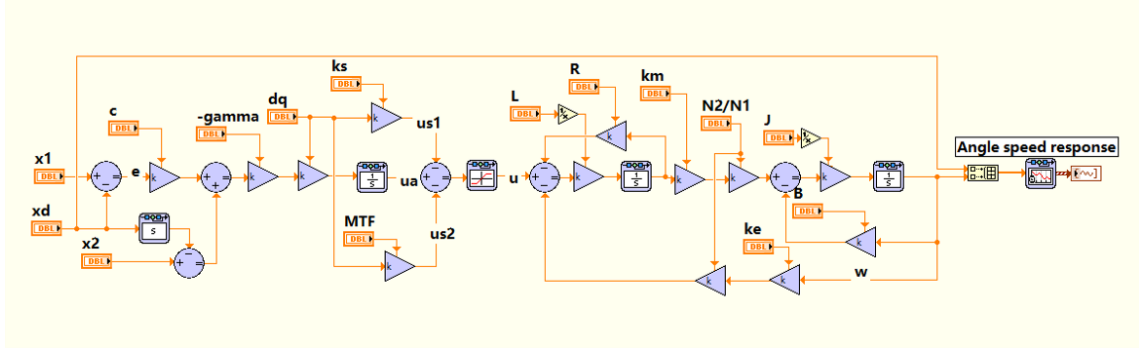


Figure 2.47. Block diagram of adaptive control in LabVIEW

The position and speed tracking plots are shown in Figure 2.48 and 2.49. The initial condition of the position and speed are set to 0.2 and 0 respectively. The position trajectory can track the reference position in a short finite time, and in the meantime, there is no oscillation in the speed tracking performance differing from the 2.44.

The control signal u with saturation in the simulation using real DC machine parameters is shown in Figure 2.50. Compared with Figure 2.46, the adaptive sliding mode

controller is robust enough to follow the position and speed with small oscillation and minor amplification control signal. The sliding parameter $k_s = 50$, The reaching parameter $c = 5, \gamma = 50, k = 15.01$. The DC machine parameters are in Table 2.4.

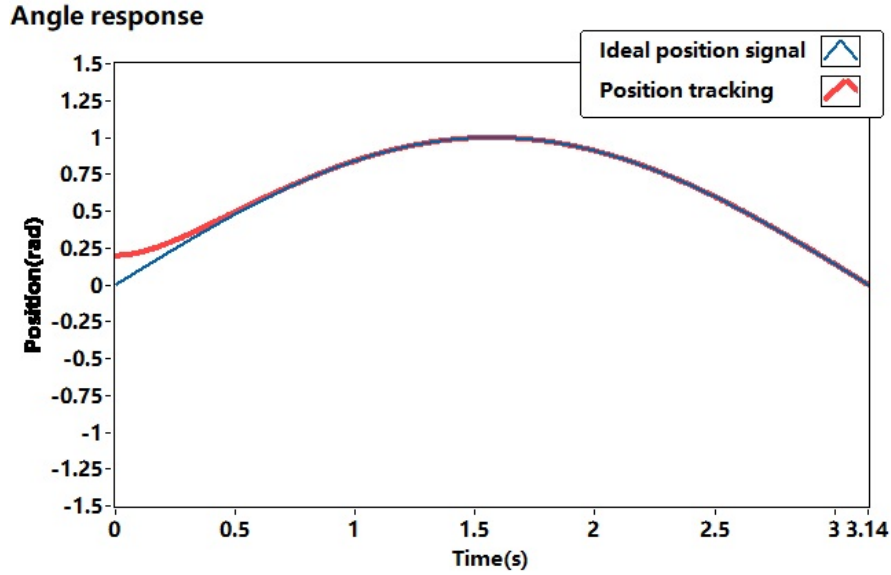


Figure 2.48. Real parameter position tracking

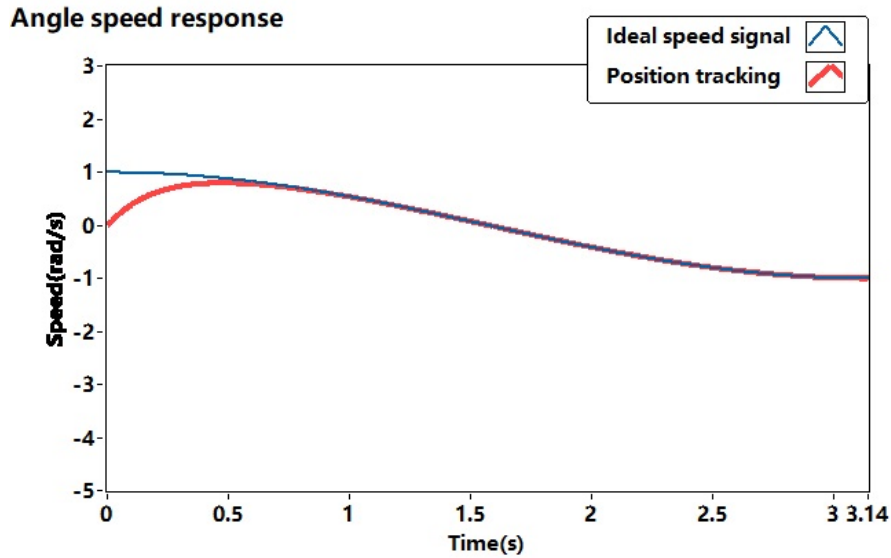


Figure 2.49. Real parameter speed tracking

In this chapter, a simple sliding mode controller with a general target simulation is introduced as a starter. And then an adaptive robust sliding mode is modeled to upgrade

the sliding mode to get better performance on oscillation and amplification. The last simulation uses the DC machine's real parameter on the adaptive robust sliding mode. It actually has a better performance on oscillation and amplification. Another main contribution of this section is the Bond Graph representation of the adaptive robust sliding mode controller for mechatronics engineering subject education. The Bond Graph representation presents the synergy of the mechatronics system from a combination of cross-interdisciplinary graphical language points of view.

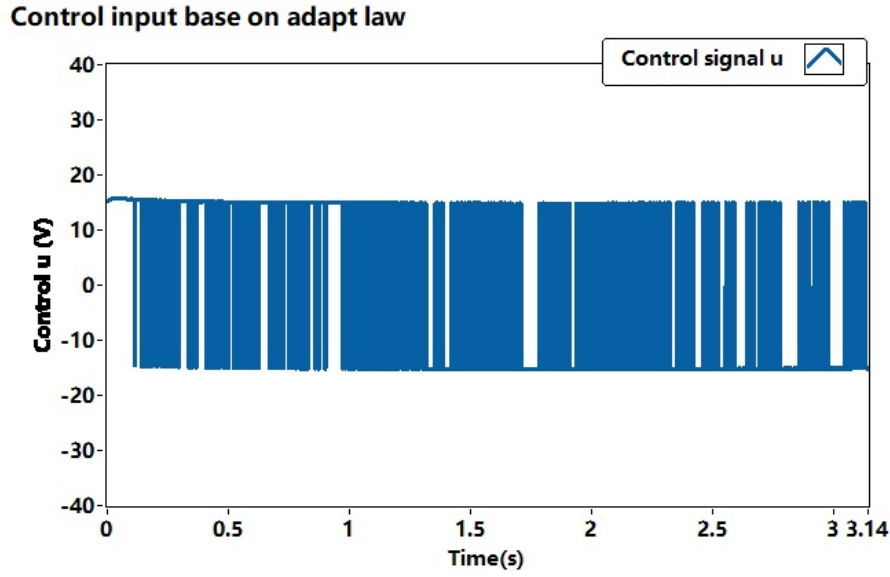


Figure 2.50. Real parameter control signal

2.4 Lagrangian and Hamiltonian Bond Graph

The Bond Graph plays a critical role in representing dynamic motion control systems, Newton's laws of motion provide a useful and practical guideline for understanding movement. In addition to applying the Bond Graph to traditional motion control, it also provides a representation of the Lagrangian and Hamiltonian when analyzing mechanics involving complex forces and generalized coordinates.

The traditional analysis of dynamic systems uses direct modeling when the models are sufficiently simple. Complex methods are utilized when addressing more advanced models. The principles of mass and momentum conservation are directly applied in direct

modeling techniques. The “energy methods” are the use of Lagrange’s and Hamilton’s equations [113].

To enhance the understanding of Lagrangian equations and their applications, The bond graph integrated with Lagrange’s equations is presented for the physical system in terms of energy and power. The fundamental form of Lagrange’s bond graph incorporates simplified transformed equations and essential variables. Additionally, the bond graph improves the energetic structure and functional behavior of the system.

The numerical aspects of the Lagrangian equations can be emphasized as follows. If we view the system as a collection of prime points, the position of each prime point can be determined by several independent generalized coordinates, q_i , and as a function of time t , then the change of the whole system with time can be described by the function $q_i(t)$. Denoting the derivative of $q_i(t)$ with respect to time as $\dot{q}_i$, each $q_i(t)$ can be solved by the Lagrange equation if all $q_i, \dot{q}_i$ at the initial moment are given [113]:

$$\frac{d}{dt} \frac{\partial L}{\partial \dot{q}_i} = \frac{\partial L}{\partial q_i} \quad (i = 1, 2, 3, \dots, N) \quad (2.44)$$

Where, L is the lagrangian of the system, which is equal to the difference between the kinetic energy of the system and the potential energy. We consider the q_i and $\dot{q}_i$ as the q and $\dot{q}$ for the convenience. Then the Lagrangian of the system is shown in the equation 2.45.

$$L(q, \dot{q}, t) = T(q, \dot{q}, t) - V(q, t) \quad (2.45)$$

Where the T presents the kinetic energy of the system, V donates the system’s potential energy. The conserved quantity in the system is called $\frac{\partial L}{\partial \theta}$, as the θ equals zero in the Lagrangian equation right side [113].

$$\frac{d}{dt} \frac{\partial L}{\partial \dot{\theta}} = \frac{\partial L}{\partial \theta} = 0 \quad (2.46)$$

In this situation, if the Lagrangian does not depend on a generalized coordinate q_i , then the generalized momentum p_i is a conserved quantity known as a cyclic coordinate. The generalized momentum known as conjugate momentum is defined as: [113]

$$p_i = \frac{\partial L}{\partial \dot{q}_i} \quad (2.47)$$

The Bond Graph of the Lagrange equation can be represented in Figure 2.51 based on the theory of the Lagrangian equations above.

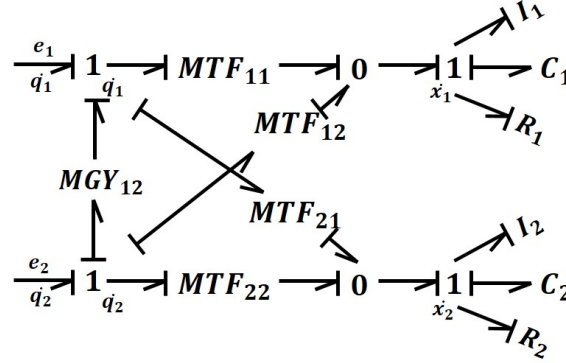


Figure 2.51. *general Lagrangian bond graph [115]*

The Lagrangian Bond Graph above is detailed but complicated, so it is necessary to introduce a simplified version. Before introducing the alternate form of the Lagrangian bond graph, the C-field bond graph should be illustrated in the following Figure 2.52. There are two sources of effort as the inputs, which are the two independent generalized coordinates. In the meantime, the passive element is the compliance. This simplification version is the compliance field or C-field. The Inertance field shares the same logic as the compliance field.

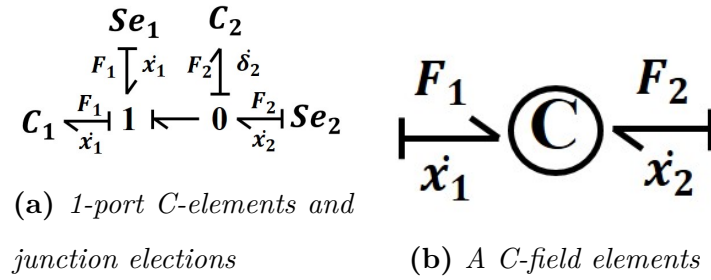


Figure 2.52. *1-port C-element and c-field element*

There is a simplified form of the Lagrange bond graph. The Lagrangian Bond Graph obeys the same theory as the compliance field. The Lagrangian Bond Graph in Figure

2.51 could be simplified to the alternate form of the Lagrangian bond graph as Figure 2.53.

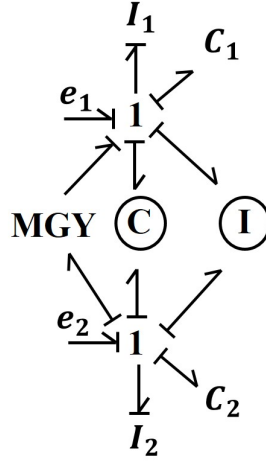


Figure 2.53. *Lagrangian bond graph alternate form [115]*

Lagrange's equations are a powerful method for the modeling in many fields. Lagrange's equations can represent the energy and power involving only generalized displacements and velocities. The bond graph is also a powerful tool in the modeling subject by the graphical language of the energy storages and the effort flows.

A simple example could explain the benefit of the Lagrangian Bond Graph shown in Figure 2.54. The length of the spring is l , and it has the length $l + x(t)$ with a mass m attached. The angle in the figure is θ . The Lagrange equations of the pendulum motions between $x(t)$ and θ is shown in the following:

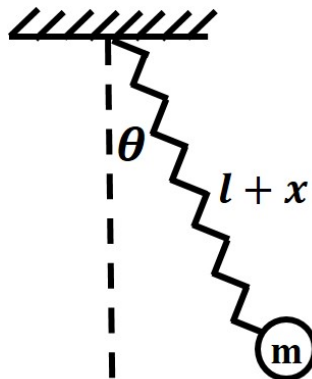


Figure 2.54. *Pendulum*

The kinetic energy of the pendulum motion system is:

$$T(x, \theta) = \frac{1}{2}m(\dot{x}^2 + (l + x)^2\dot{\theta}^2) \quad (2.48)$$

The potential energy contains the spring and the gravity:

$$T(x, \theta) = -mg(l + x)\cos\theta + \frac{1}{2}kx^2 \quad (2.49)$$

The Lagrangian of the system is:

$$L = T(x, \theta) - T(x, \theta) = \frac{1}{2}m(\dot{x}^2 + (l + x)^2\dot{\theta}^2) + mg(l + x)\cos\theta - \frac{1}{2}kx^2 \quad (2.50)$$

By analyzing the schematics of the system, there are two variables θ and x . The Euler-Lagrange equations are shown in the following:

$$\frac{d}{dt}\left(\frac{\partial L}{\partial \dot{x}}\right) = \frac{\partial L}{\partial x} \quad \rightarrow \quad m\ddot{x} = mg\cos\theta + m(l + x)\dot{\theta}^2 - kx \quad (2.51)$$

$$\frac{d}{dt}\left(\frac{\partial L}{\partial \dot{\theta}}\right) = \frac{\partial L}{\partial \theta} \quad \rightarrow \quad m(l + x)\ddot{\theta} + 2m\dot{x}\dot{\theta} = -mg\sin\theta \quad (2.52)$$

The numerical mathematical Lagrange equations are complicated compared with the Bond Graph. There is only one generalized coordinate in the system, which is the reason for only 1-junction in Figure 2.55.

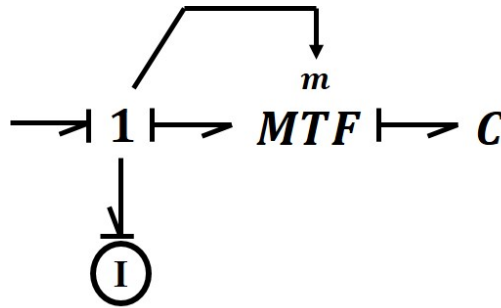


Figure 2.55. *Lagrangian Bond Graph of pendulum*

Another classic example that serves as teaching material for the mechanism system is illustrated in the figure below 2.56.

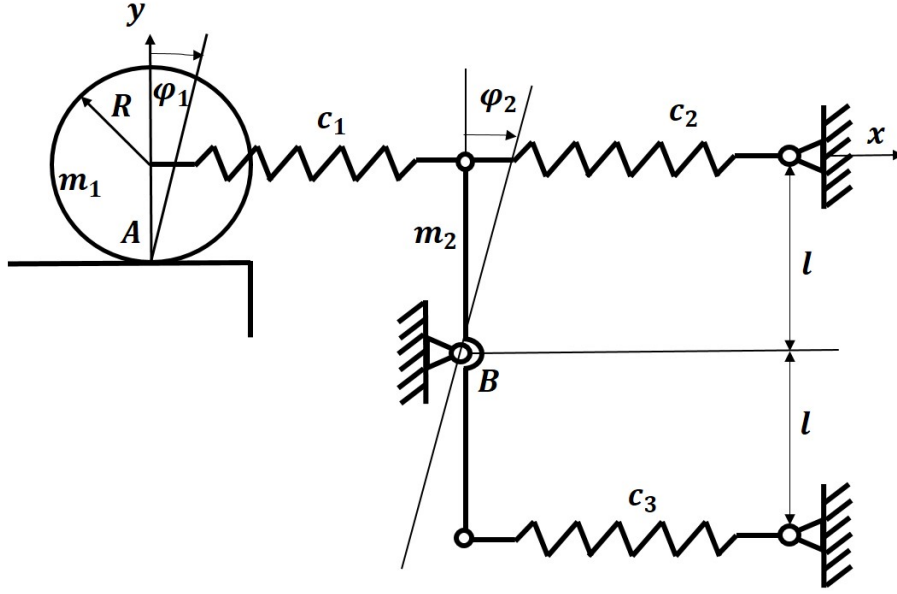


Figure 2.56. *Higher DOF linear dynamical system*

If sufficiently simple, the traditional method for high-degree-of-freedom (DOF) spatial dynamics could utilize modeling with Lagrangian methods. The Bond Graph can be directly converted into a model by providing the structural meaning of the model.

The Lagrange equations are shown in the following:

$$\frac{d}{dt}\left(\frac{\partial E}{\partial \dot{q}_i}\right) - \frac{\partial E}{\partial q_i} = \sum Q_{ci} \quad (i = 1, 2) \quad (2.53)$$

Where $\dot{q}_i = \omega_i$ represents the angular velocity. E is the system's kinetic Energy, and the Q_{ci} donates the general forces.

$$\begin{aligned} E &= \frac{1}{2}J_A\omega_1^2 + \frac{1}{2}J_B\omega_2^2 \\ &= \frac{1}{2}J_A\dot{\phi}_1^2 + \frac{1}{2}J_B\dot{\phi}_2^2 \\ &= \frac{1}{2}\left(\frac{3}{2}m_1R^2\right)\dot{\phi}_1^2 + \frac{1}{2}\left(\frac{1}{3}m_2l^2\right)\dot{\phi}_2^2 \end{aligned} \quad (2.54)$$

J_A and J_B are the system inertia. The kinetic energy of the system consists of the inertia sum of the disk and the stick.

$$\begin{aligned}
 U &= U_1 + U_2 + U_3 \\
 &= \frac{1}{2} \frac{(l\varphi_2 - R\varphi_1)^2}{c_1} + \frac{1}{2} \left(\frac{l^2}{c_2} + \frac{l^2}{c_3} \right) \varphi_2^2
 \end{aligned} \tag{2.55}$$

U represents the potential energy of the spring, calculated as the deformation squared divided by the spring's stiffness.

$$Q_{ci} = -\frac{dU}{dq_i} \tag{2.56}$$

In 2.56, there are only two generalized coordinates φ_2 , and φ_1 . For those two generalized coordinates, only one input is applied to the disk to generate the φ . Then the spring C_1 connects to the long stick to trigger the other two springs. The representation of the Lagrangian Bond Graph is shown in Figure 2.57. The analysis of dynamic mechanisms is a topic in mechatronics engineering. The Bond Graph is crucial for modeling and simulating mechanisms. It emphasizes the synergy property of the Bond Graph [113].

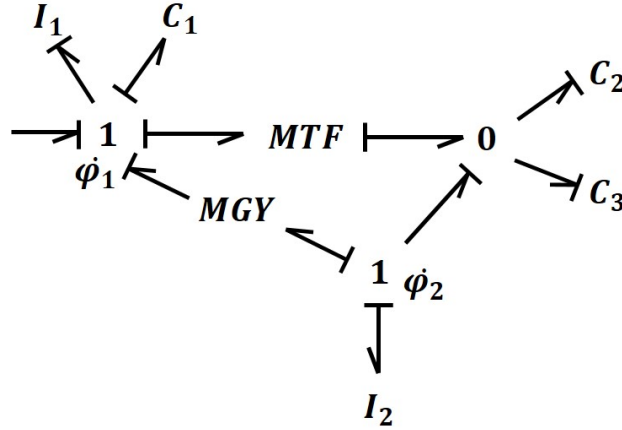
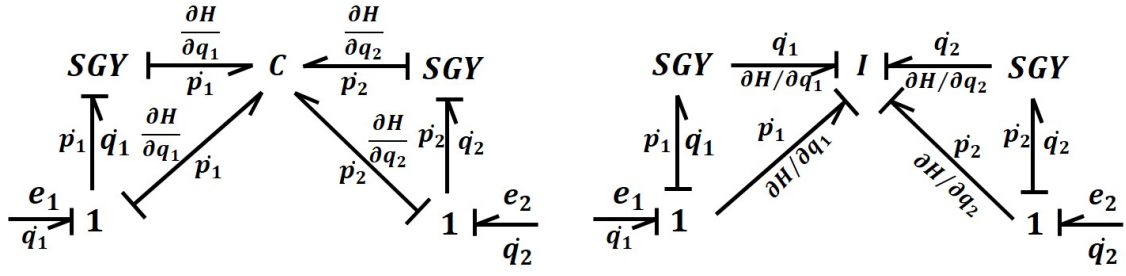


Figure 2.57. *Lagrangian Bond Graph of the mechanism*[113]

Hamilton's equations are shown to be the conventional bond graph. The Hamiltonian bond graphs directly represent Hamilton's equations. The multiport I element stands for the generalized velocity or flows, which is the algebraic function of the generalized momentum vector. The same theory applies to the multiport C element, it represents the force or effort, and they are the algebraic function of the generalized displacement vector.



(a) *Hamiltonian Bond graph for c element* (b) *Hamiltonian Bond graph for I element*

Figure 2.58. *Hamiltonian Bond graph [115]*

Lagrangian and Hamiltonian bond graphs are a powerful tool for the user to understand the model that applies broadly to the energy system.

2.5 Conclusion

The case studies in this chapter range from simple to complex, from numerical traditional methods (ODEs) to analytical strategies (Bond Graph) to illustrate the outstanding contribution of Bond Graph to the mechatronics education method.

The benefits of the Bond Graph are demonstrated in the case of comparison between the traditional method and the Bond Graph. Compared with the traditional methods, the Bond Graph provides a graphical tool to skip the mathematical calculation analysis directly to the modeling results. Skipping the step does not mean disregarding the entire mathematical process. Instead, the Bond Graph offers students the opportunity to understand the mathematical process by observing the modeling results, which can enhance their grasp of traditional calculations. Efficient application method usages are characterized in the field of PID and SM controller Bond Graph representation. Lagrangian Bond Graph equation's applicability for more complex case studies such as mechanism dynamics analysis.

The Bond Graph prepares mechatronics engineers for complex challenges and promotes problem-solving and critical-thinking skills. Additionally, the Bond Graph provides an effective method of bridging the gap between theoretical knowledge and practical application in mechatronics engineering education.

3

Numerical and Analytical of the Disturbance Observer

3.1 Direct and Inverse Disturbance Observer

The disturbance removal is a critical step in the dynamic system control. The disturbance observer is based on the transfer function of the inverse model. Compensation for the equivalent is introduced in the control process to achieve complete control of the disturbance. In this chapter, a direct model of disturbance observer is proposed to be compared with the inverse model disturbance observer. The direct model disturbance observer can work without any additional filter, which simplifies the design and the implemented controlling process.

In the meantime, the Bond Graph could represent the direct and inverse disturbance observer. The bond graph presents the powerful functions of illustrating control theory and multiple domains. This chapter is divided into two main parts, the numerical and the analytical of the Disturbance observer. The numerical of the disturbance observer describes the disturbance observer from the mathematical method of thinking, in the meantime, the analytical of the disturbance observer provides a novel representation of the disturbance observer from a graphical Bond Graph point of view.

3.1.1 Numerical of the Inverse disturbance observer

The simplified motor model is shown in equations 3.1 and 3.2, where the input and output are described using u and y . The nominal parameters T_n and G_n are used in the inverse disturbance observer model. The d is the disturbance signal and it is estimated by $\hat{d}$.

$$y(s) = \frac{G_m}{1 + sT_m}(u(s) + d(s)) \quad (3.1)$$

$$d = \frac{1 + sT_m}{G_m}y - u \quad \hat{d} = \frac{1 + sT_n}{G_n}y - u \quad (3.2)$$

The main operation principle of the simple disturbance observer can be described in Figure 3.1. The mechanical time constant T_m and the gain G_m consist of the motor model in the upper part of the block diagram. The T_n and the G_n are the estimated reciprocal of the motor model in the lower part of the block diagram.

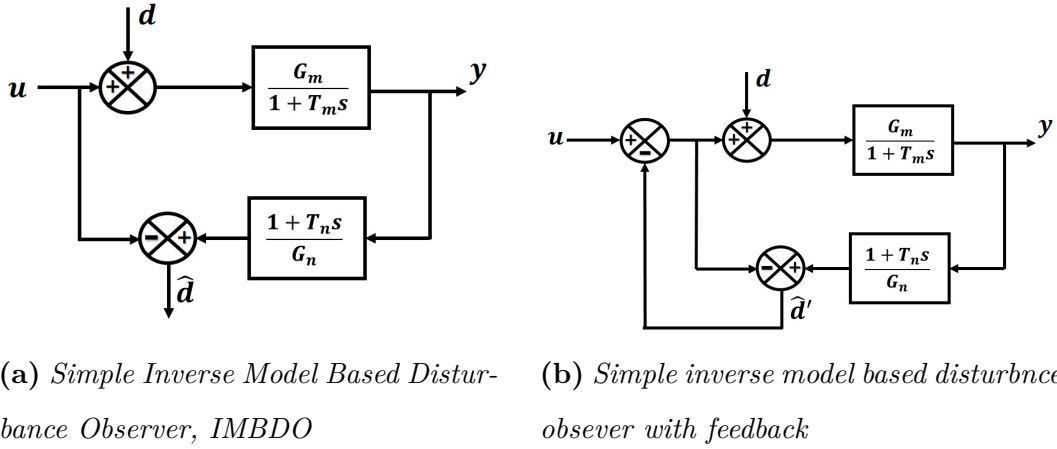


Figure 3.1. Inverse model disturbance observer

There are difference between the simulation system and the real system model, which are considered as the parameter disturbance presented in 3.3.

$$T_m = T_n + \Delta T_n \quad G_m = G_n + \Delta G_n \quad (3.3)$$

The difference ΔT_n and ΔG_n are limited to estimate the disturbance signal. The estimated disturbance output $\hat{d}$ are the feedback with the compensation purpose of the

disturbance signal d . The output signal y can be calculated as the transfer function $\frac{G_n}{1+T_n s}$ from the control signal input u in Figure 3.1(b).

The differential term could amplify the noise of system which is a problem needs to be solved. Theoretically, the influence of the noise can be eliminated by the low-pass filter $w(s)$ in the feedback branch, which is shown in Figure 3.2.

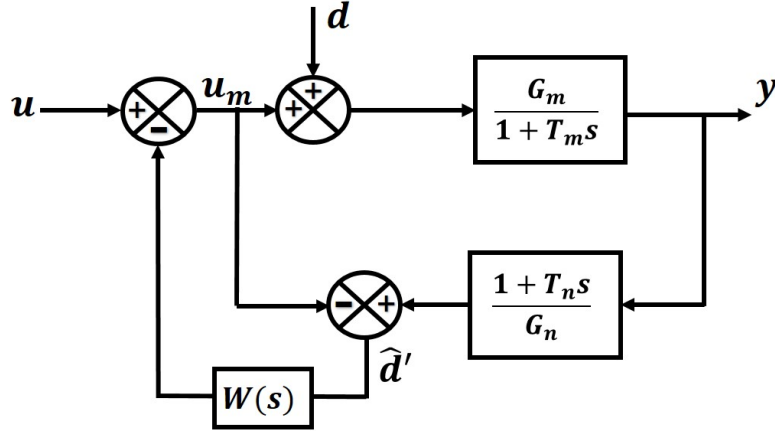


Figure 3.2. simple IMBDO with filter feedback

For the purpose of keeping useful signal in the input, the reciprocal of the time constant T_m should be smaller than the cutoff frequency of $W(s)$. The disturbance signal to y , which is the transfer function absolute value can be maintained small enough at a lower frequency range, if the filter $W(s)$ is at a certain range.

3.1.2 Numerical of the Direct disturbance observer

The direct disturbance observer is an expansion of the inverse disturbance observer. In this chapter, the same parameters of the motor model are considered as in the following model case. The difference y_e is fed back to the input, the difference is between the ideal model and the disturbance estimated model in Figure 3.3.

The block diagram of the direct disturbance observer is shown in figure 3.3

The difference signal y_e is small to obtain a small value of the feedback signal $\hat{d}$ if K is big enough. In this case, the signal $\hat{d}$ could present the information of the parameters disturbance ΔT_n and ΔG_n . The calculation of the u to y is shown in the following:

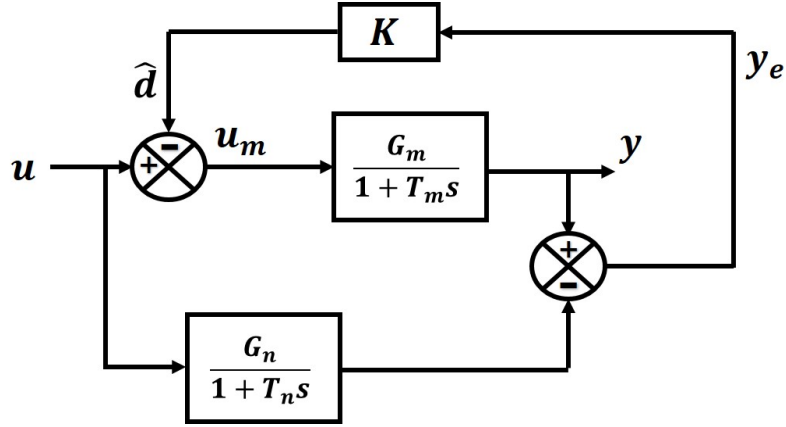


Figure 3.3. *Direct Model Based Disturbance Observer*

$$\begin{aligned}
 \lim_{K \rightarrow \infty} \left(\left(1 + \frac{KG_n}{1 + sT_n} \right) \frac{\frac{G_m}{1 + sT_m}}{1 + K \frac{G_m}{1 + sT_m}} \right) &= \lim_{K \rightarrow \infty} \left(\frac{1 + sT_n + G_n K}{1 + sT_n} \frac{G_m}{sT_m + KG_m + 1} \right) \\
 &= \lim_{K \rightarrow \infty} \left(\frac{G_n + \frac{1 + sT_n}{K}}{1 + sT_n} \frac{G_m}{G_m + \frac{1 + sT_m}{K}} \right) \\
 &= \frac{G_n}{1 + sT_n}
 \end{aligned} \tag{3.4}$$

Output can be influenced by the disturbance $d(t)$:

$$\lim_{K \rightarrow \infty} \left(\frac{\frac{G_m}{1 + sT_m}}{1 + K \frac{G_m}{1 + sT_m}} \right) = 0 \tag{3.5}$$

This can explain the fact that the feedback signal $\hat{d}$ contains information about finite parameters and input disturbance.

3.2 Bond Graph Representation of Direct and Inverse Disturbance Observer

After introducing the numerical representation of the inverse and direct disturbance observer, it is time to start the analytical representation of the inverse and direct disturbance observer. The method is to use the Bond Graph as a graphical language to describe the details of the disturbance observer methodologies. For the Bond Graph, the students

Bond Graph Representation of Direct and Inverse Disturbance Observer

could get a comprehensive understanding of the disturbance observer compared with the mathematical method.

The conversion of the disturbance observer is based on the principle of the Bond Graph and logical calculation. It is all from the basic relationship of the 1 – *junction* and causality direction representation.

The Bond Graph of the inverse disturbance observer is shown in figure 3.4

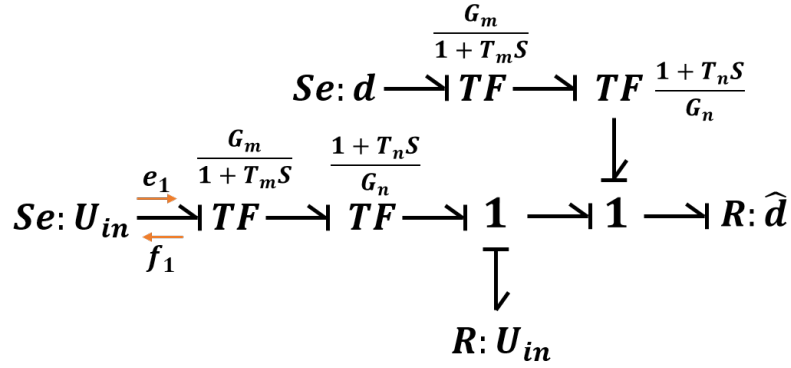


Figure 3.4. *Bond Graph inverse disturbance observer*[113]

The Bond Graph shown in Figure 3.5 is based on the structure of Figure 3.4. The first 1 – *junction* inside is the feedback loop in the block diagram 3.1(b). The red arrows show the direction of the effort and flow. The causality means the direction of the effort, and the direction of the flow is opposite to the effort.

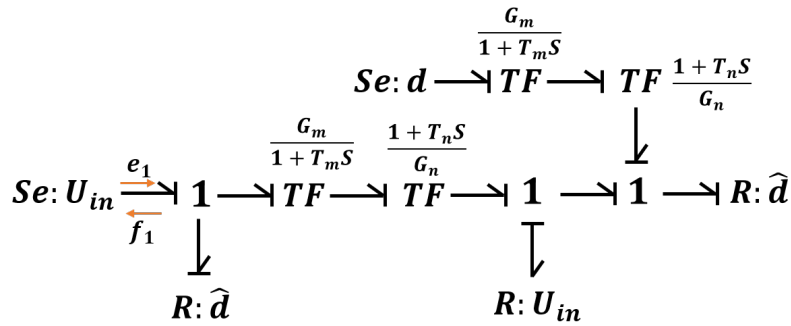


Figure 3.5. *Bond Graph simple inverse model based disturbance observer with feedback*

The block diagram representation of the inverse disturbance observer is shown in Figure 3.6, and the inverse disturbance observer with the feedback can be described in

Figure 3.7. In the LabVIEW programming, the feedback node is used to avoid errors and fulfill the completion of the programming.

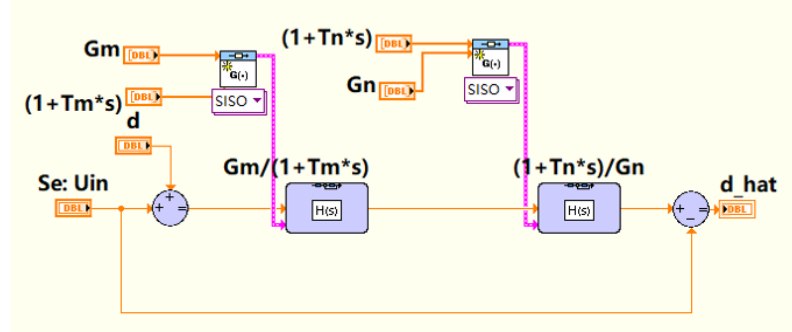


Figure 3.6. Block diagram of simple inverse model based disturbance observer

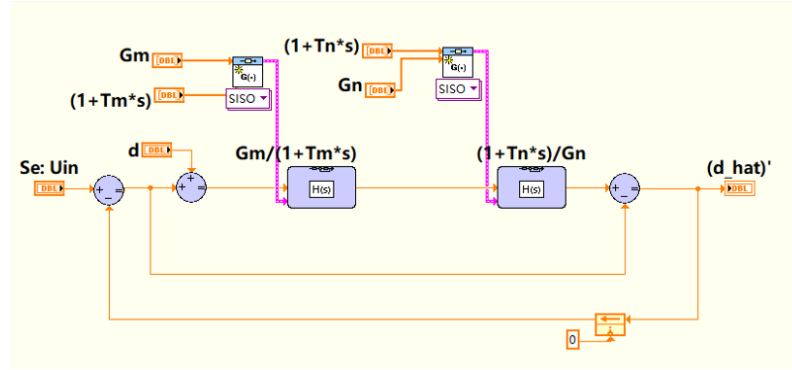


Figure 3.7. Block diagram of simple inverse model based disturbance observer with feedback

The Bond Graph of the direct disturbance observer is shown in figure 3.8. The conversion of the Bond Graph direct disturbance observer obeys the principle of the Bond Graph knowledge, which could realize the function of the feedback and basic subtraction from the block diagram in Figure 3.3. The same R elements represent the same value, which could be converted by the GY or TF .

3.3 Comparison Simulation Results

The discrete-time transfer function $W_{dm}(z)$ is shown in the equation 3.6. Where the $M_m(z)$ is the torque and the $\omega(z)$ is the velocity.

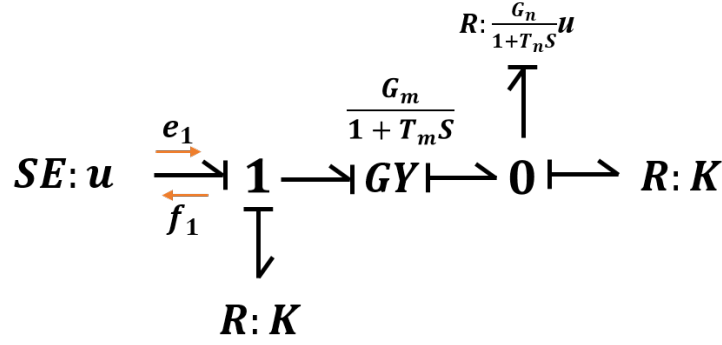


Figure 3.8. Bond Graph of direct model disturbance observer

$$W_{dm}(z) = \frac{\omega(z)}{M_m(z)} = \frac{0.06}{z - 0.6} T_s = 2ms \quad (3.6)$$

T_s donates the sampling time of the simulation system. Then the $W_{cm}(s)$ presents the continuous transfer function as shown in equation 3.7.

$$W_{cm}(s) = \frac{\omega(s)}{M_m(s)} = \frac{0.15}{0.004s + 1} \quad (3.7)$$

The block diagram of the motor model is shown in Figure 3.9.

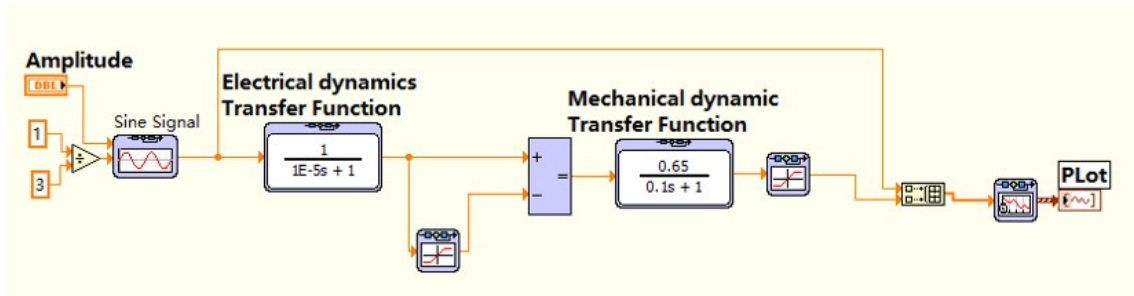


Figure 3.9. Block Diagram of the motor

Where the electrical dynamics is presented as $\frac{1}{T_e s + 1} = \frac{1}{1e^{-5}s + 1}$. The torque electrical dynamics is $T_e = 0.1ms$. In the meantime, Torque mechanical is $T_m = 20ms$. And the $\frac{G_m}{T_m s + 1} = \frac{0.65}{0.1s + 1}$.

The first-order reference motor model can be considered as in the following:

$$J\dot{\omega}(t) = u_m(t) - B\omega(t) \quad (3.8)$$

Where the J donates the inertia of the electrical part and the B is the viscous friction constant of the motor model. U_m is the input of the reference model, and the relationship of the parameters is shown in the following 3.9:

$$T_m = \frac{J}{B} \quad G_m = \frac{T_r}{100J} \quad (3.9)$$

The block diagram of the direct model and the inverse model of the disturbance observer is shown in Figure 3.10 and 3.11.

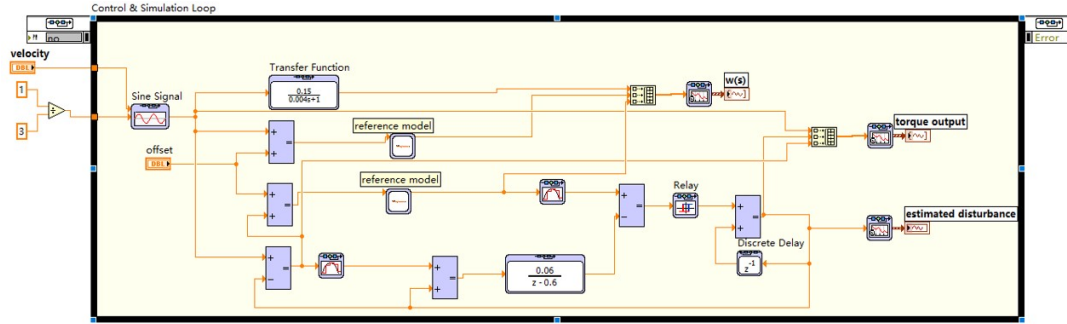


Figure 3.10. Block Diagram of the direct model of the disturbance observer

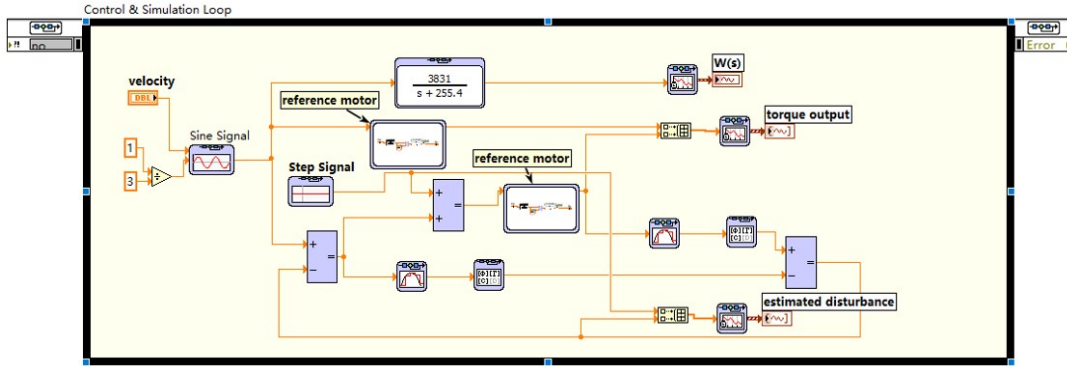


Figure 3.11. Block Diagram of the Inverse model of the disturbance observer

Matlab Simulink serves the same purpose as LabVIEW since both of the platforms share the same core. The Simulink direct and inverse models of the disturbance are shown in Fig. 3.12 and Fig. 3.13 for the comparison with the block diagram in LabVIEW.

Simulink and the LabVIEW codes are converted from the block diagram generated by the Bond Graph or mathematical equation. Both of the two methods can achieve the simulation purpose with a slightly different menu setting.

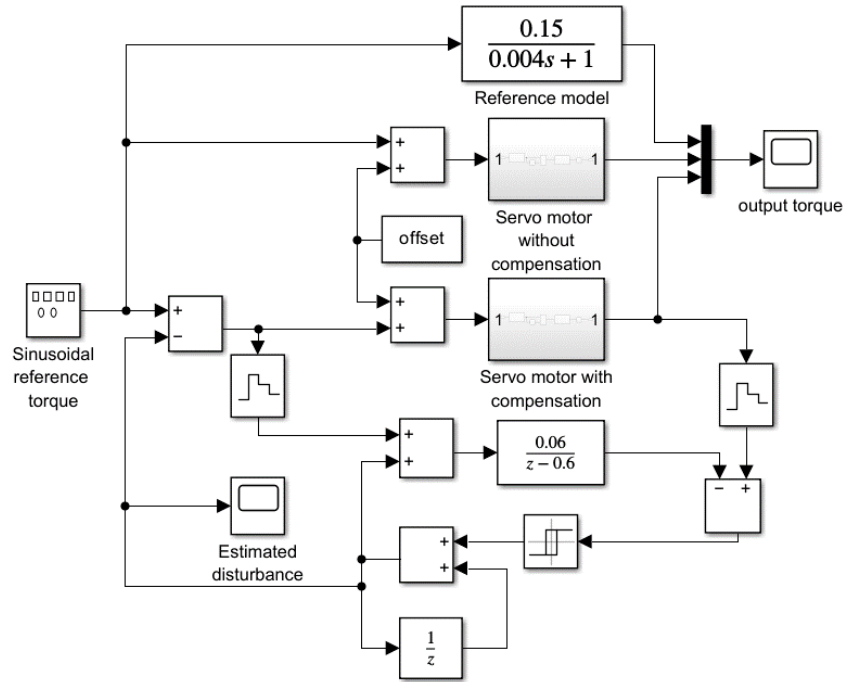


Figure 3.12. Simulink of the direct model of the disturbance observer

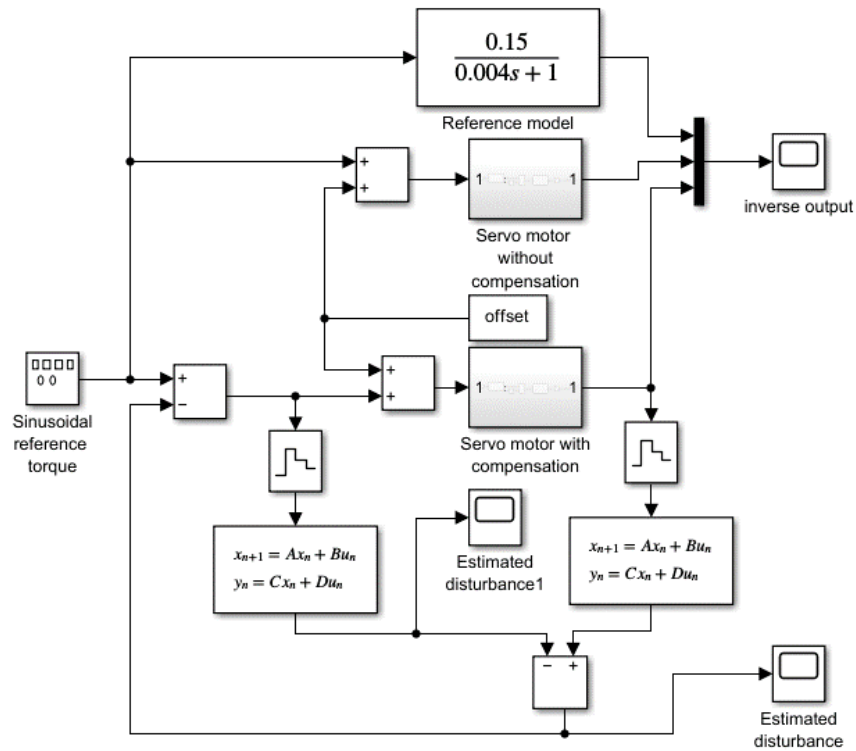


Figure 3.13. Simulink of the inverse model of the disturbance observer

There are two measurements of the results, the input u is the sinusoidal, representing the torque reference signal. The first two sets of the results show the amplitude of u is 15% and 20%. An operational amplifier presents the loop of control with an armature current with an uncompensated offset. The acceleration torque is shifted vertically along the positive direction. The operational amplifier offset results in an asymmetric uncompensated velocity ω_{nc} under the disturbance observer off circumstance. The real motor speed is faster than the ideal speed ω_{id} .

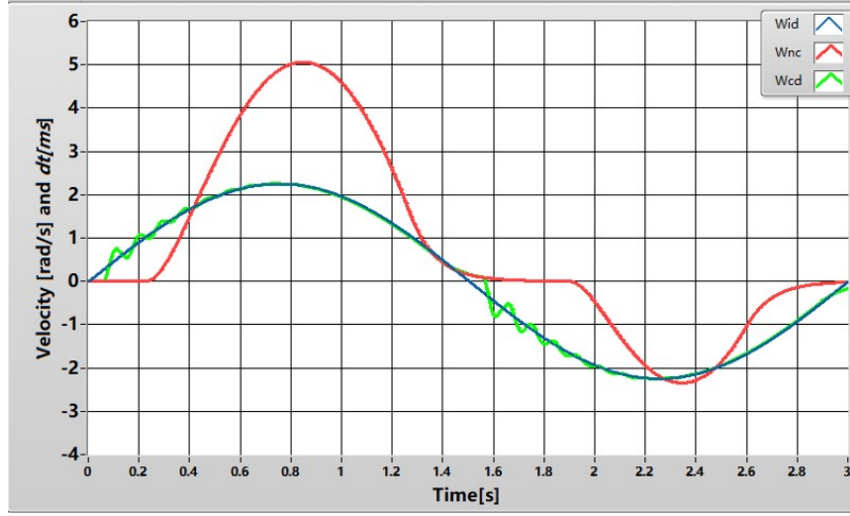


Figure 3.14. *simulation result of the IMDOB with $u=15$*

The first set of comparison results are shown in Figure 3.14 and 3.15. Compared with the results of the inverse disturbance observer and the direct disturbance observer. It plots that the direct disturbance observer presents a better stable performance than the inverse disturbance observer with a small chattering during the crossing of the horizontal line. The second set of the results is shown in Figure 3.16 and 3.17 with the amplitude set to 20.

The direct disturbance observer has a small chattering when it crosses the horizontal line compared with the inverse disturbance observer. At the same time, the direct disturbance observer has a faster reaction to the sudden changes in the disturbance with less sensitivity in sampling. Estimate disturbance is introduced as the feedback compensator of the disturbance signal. The disturbance estimator carries not only the information of the real disturbance signal but also the deviation of the parameter. The output signal

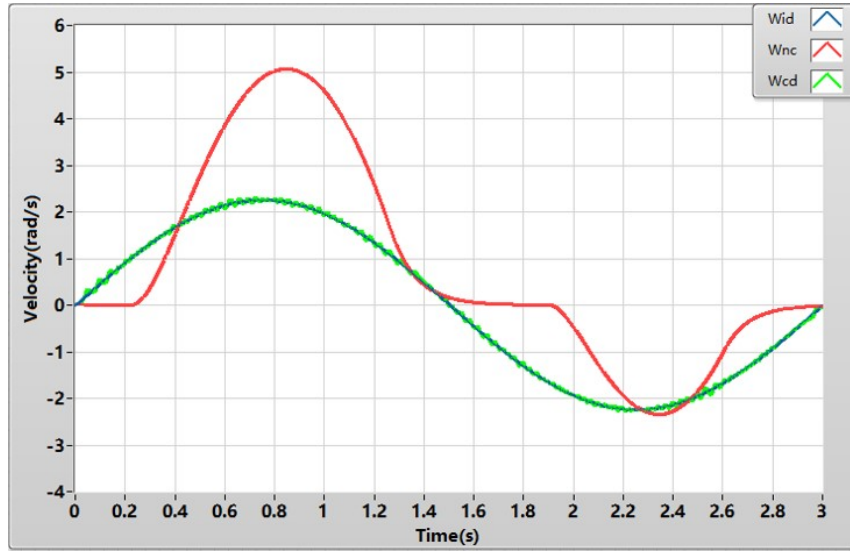


Figure 3.15. simulation result of the DMDOB with $u=15$

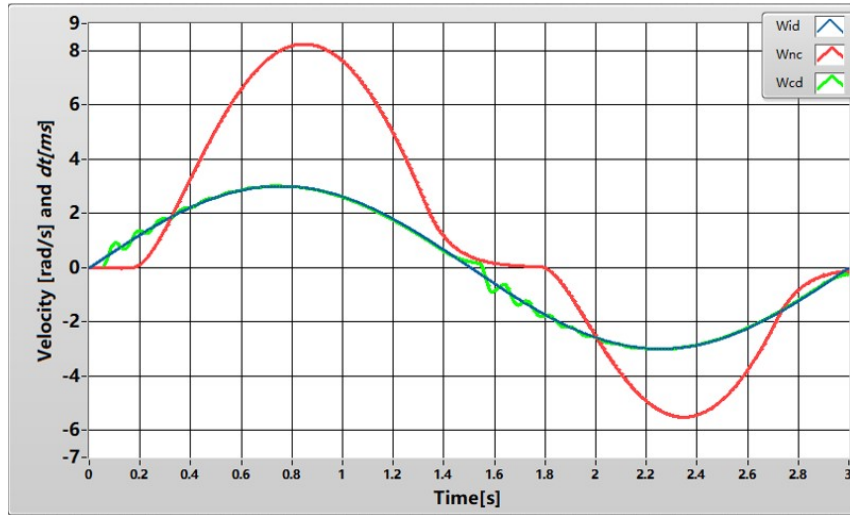


Figure 3.16. simulation result of the IMDOB with $u=20$

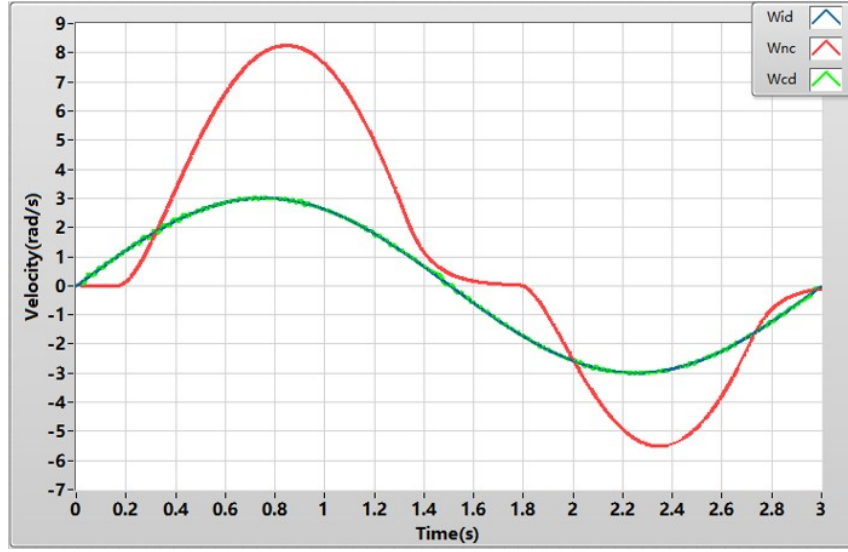


Figure 3.17. *simulation result of the DMDOB with $u=20$*

does not rely on the disturbance signal after the disturbance estimation calculation.

In reality, the noise is amplified by the differentiation in the dynamic system, which causes accuracy problems. The low-pass filter on the feedback branch is necessary to eliminate the amplification of the noise.

3.4 Conclusion

In this chapter, a comparison of the inverse disturbance observer and the direct disturbance observer is presented under the non-realtime motor dynamic system. Both of the methods serve the same purpose with the same results with a slight difference. Another main contribution in this chapter is the Bond Graph representation of the direct and inverse disturbance observer. The efficient education method of the Bond Graph is demonstrated in the case of the inverse and direct disturbance observer Bond Graph graphical representation. The demonstration of the two methods of Bond Graph representation proved the importance of the Bond Graph synergy in the Mechatronics education method.

4

Test Results and Conclusions

The Bond Graph is a powerful and more acceptable graphical language for the mechatronics engineering students. Strong evidence is more persuasive than a speech, so a proof test over three years has been done among the mechatronics engineering students in the 'Modeling and simulation' subject. In the final test of the 'modeling and simulation' subject, the mechatronics engineering students responded that the Bond Graph is much easier than the traditional mathematical technique to solve the practical dynamic system in mechatronics engineering.

4.1 Test Results of Mechatronics subject over three years

There are three questions for the students to be solved in the final exam of the 'modeling and simulation'. The students are requested to solve each question using two methods, the Bond Graph, and the traditional mathematical method. In this case, a high score could claim a better and more acceptable solution for the students to study the subject of mechatronics engineering.

The dissertation addresses educational methods, which fall under social science. This is why a statistical approach is chosen to validate the results. The performance of the proposed method has been evaluated for selected student groups based on specific activities. The validation test was repeated three times due to the absence of a control group.

The test questions were prepared by honorable professors in the Mechatronics department, Engineering Faculty, University of Debrecen. The test questions are corrected by 3 persons in the department, three lecturers who are in charge of the ‘modeling and simulation’ subject. One lecturer is a professor, one is a master’s student, and the last one is PhD student. After correcting the answers, all the papers are sent back to the professor for final checking. In the end, all the analysis and the t-test are done by the candidate.

For the first-year final test, there are 21 students in the ‘modeling and simulation’ class, all the student’s test results were collected to compare the traditional mathematical method and the Bond Graph method. The question should be from 1(fail) to 5(excellent). The results were well collected and data was analyzed using mean and average values shown in Table 4.1. Based on the response of the first-year chart, the average difference of each question between the Bond Graph and to ODE method has a variety of differences by 16%, 26%, and 6% respectively.

Table 4.1. *The first-year test results*

	Question 1	Question 2	Question 3
ODE average	3.57	3.57	3.95
Bond Graph average	4.38	4.86	4.24
ODE mean	3.28	3.35	3.56
Bond Graph mean	4.31	4.83	4.06
Average(Bond Graph-ODE) difference	0.81	1.29	0.29
Mean(Bond Graph-ODE) difference	1.03	1.48	0.51
Average(Bond Graph-ODE) difference%	16%	26%	6%
Mean(Bond Graph-ODE) difference%	21%	30%	10%

The test result for the second year is a 38-student sample. The numerical analysis is

Table 4.2. *The Second-year test results*

	Question 1	Question 2	Question 3
ODE average	3.17	2.21	3.65
Bond Graph average	4.26	3.03	4.63
ODE mean	3.19	1.72	3.14
Bond Graph mean	3.84	2.47	4.35
Average(Bond Graph-ODE) difference	1.09	0.82	1.00
Mean(Bond Graph-ODE) difference	0.64	0.72	1.21
Average(Bond Graph-ODE) difference%	22%	16%	20%
Mean(Bond Graph-ODE) difference%	13%	14%	24%

shown in Table 4.2. The students' scores have a 22%, 16%, and 20% increase when using the Bond Graph compared with the traditional ODE methods.

For the third year, there were 37 students in the modeling and simulation class. Compared with the traditional ODEs method, the students gained 25%, 39%, and 33% more scores on each question.

Table 4.3. *The Third-year test results*

	Question 1	Question 2	Question 3
ODE average	3.14	1.70	1.65
Bond Graph average	4.41	3.65	3.30
ODE mean	2.75	1.49	1.39
Bond Graph mean	3.97	3.15	2.65
Average(Bond Graph-ODE) difference	1.27	1.95	1.65
Mean(Bond Graph-ODE) difference	1.27	1.66	1.26
Average(Bond Graph-ODE) difference%	25%	39%	33%
Mean(Bond Graph-ODE) difference%	24%	33%	25%

For the static analysis, the comparison of each year as a horizontal analysis is necessary. In the meantime, the vertical analysis is essential for the proof. For these three years sample, the number of students has grown, and the difference between the Bond Graph and the traditional ODEs has steadily increased. On the other hand, it actively demonstrates that the Bond Graph donates an advantage in mechatronics engineering subjects teaching.

The histogram of the three-year result comparison is shown in Figure 4.1. In the histogram, the students surely got a higher score when they used the Bond Graph method as the question solution. It reflects from the side that the Bond Graph teaching method is a more acceptable and appropriate technique for the mechatronics study. It directly

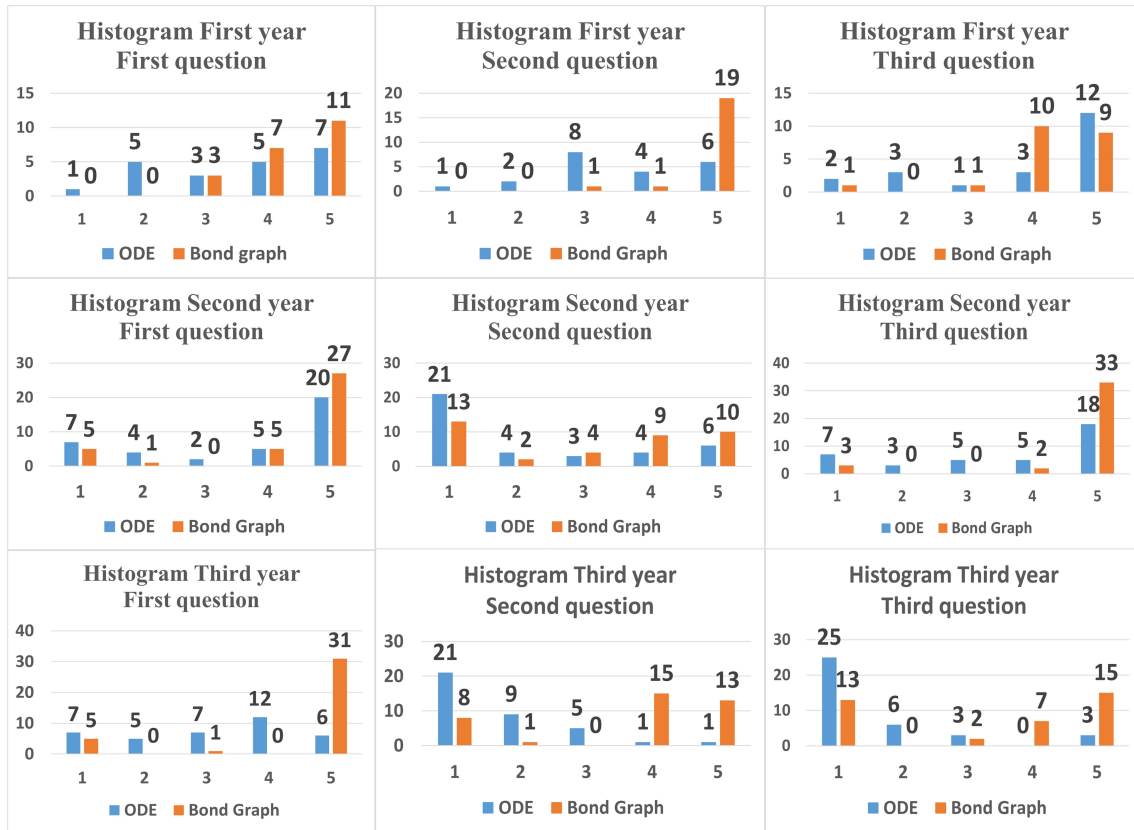


Figure 4.1. Histogram of the three questions results over three years

reflects that the Bond Graph is easier than the traditional ODEs method in the "modeling and simulation" subject. On the other hand, it does mean the Bond Graph method could replace the ODEs method in daily education and study, but it provides a novel graphical point of view of the dynamic system. The Bond Graph makes it a practical tool in mechatronics subject and a handy tool for researchers to use.

4.2 T-Test for the results

The Bond Graph graphical method and the traditional mathematical teaching method shared the same result in simulation and minor differences in details. In this case, It becomes a problem to distinguish these two methods. It is essential to figure out a persuaded solution between the Bond Graph and traditional methods. A t-test is a classical test that could provide a significant difference between the Bond Graph teaching method and the

traditional teaching method in mechatronics engineering subjects. It has been used when the two sets of data follow a normal distribution like the tests' results in this dissertation.

In this section, the t-test is used to identify whether there is a significant difference between the traditional ODE method and the Bond Graph method. The null hypothesis is the acceptance level of the students for the two methods. It could reflect the same questions solved by the mechatronics engineering students using different methods.

$$t = \frac{x_1 - x_2}{\sqrt{\frac{s_1^2}{n_1} + \frac{s_2^2}{n_2}}} \quad (4.1)$$

Where x_1 donates the mean of the Bond Graph sample, s_1 is the standard deviation of the Bond Graph sample, n_1 represents the sample size of the Bond Graph; x_2 donates the mean of the ODE method sample, s_2 donates ODE's standard deviation, n_2 is the ODE sample size.

The t-test analyzed results are shown in Table 4.4.

Table 4.4. *t-test results of three questions over three years*

	Question 1	Question 2	Question 3
First-year	0.00930	0.00001	0.26690
Second-year	0.00266	0.00008	0.00004
Third-year	0.0000004	0.00000058	0.0000025

Generally, a 0.05 can be considered as a level of two samples that has a significant difference, and the t-values above can represent that there is a significant difference between the Bond Graph method and the traditional ODEs method. It proves that the Bond Graph teaching method is more acceptable for mechatronics engineering students in daily study and tests.

The test results are the following: [Three years students mod and sim test results](#)

4.3 Conclusions

The Bond Graph provides an analytical representation in mechatronics engineering compared with the numerical expression. The Bond Graph provides a novel graphical language in the education of modeling and simulation. It illustrates the linear and non-linear controllers from a graphical point of view, such as PID controllers and sliding mode controllers. The Bond Graph representation of the Lagrangian equation explicitly spreads the energy flows using a visual perspective. The modular teaching method and the visual tools help the Bond Graph enhance the synergy property in education.

In summary, Compared with the traditional methods, the Bond Graph provides a graphical tool to skip the mathematical calculation analysis directly to the modeling results. Skipping this step does not mean disregarding the entire mathematical process. Instead, the Bond Graph offers students the opportunity to understand the mathematical process by observing the modeling results, which can enhance their grasp of traditional calculations. The t-test with a three-year test of the comparison between the traditional ODE method and the Bond Graph proves that the Bond Graph is more understandable and acceptable for mechatronics engineering students.

4.4 Claims of Dissertation

The problems and claims are shown in these categories in the following:

Thesis 1: [P1] [P3] [P5] on page 108

Based on findings and Mechatronics engineering educational experience, the Bond Graph is recognized as an effective graphical tool for teaching PID and sliding mode control in Mechatronics [P1, P3]. The Bond Graph simplifies mechatronics modeling teaching methods for undergraduate students by combining modular design and visual programming language [P1, P3, P5]. Bond Graph-based graphical model representation is a novel education method as an intuitive and native language of the Mechatronics Engineering undergraduate education field, a three-year test finding from the mechatronics engineering students has proved its efficiency. Overall, a pure graphical-based educational modeling method had been proposed and verified by processes including Schematic – Bond Graph – Block Diagram – Block-oriented code. The test results are the following [P1]: [Three years students mod and sim test results](#)

Thesis 2: [P2] [P4] [P5] on page 108

The inverse disturbance observer, as a complex case study for mechatronics education, can be replaced by the direct disturbance observer[P2]. Compared with the inverse disturbance observer, the direct disturbance observer has a better performance without the additional filter. Additionally, the Bond Graph provides a unified graphical module representation for these two disturbance observers, enhancing the effectiveness of mechatronics education [P4, P5]. Furthermore, the Bond Graph with causalities is utilized by the modularity theory for data flow-oriented programming languages in mechatronics education [P4, P5]. In the meantime, the Bond Graph method has been validated by the unique representation of the disturbance observer [P4, P5].

Thesis 3: [P1] [P3] [P4] [P5] on page 108

The dissertation proposes to use the Bond Graph to modularize the modeling and simulation and enhance mechatronics education by representing traditional formulas visually [P3]. Throughout three years of mechatronics education, the Bond Graph has proven to be beneficial to mechatronics education [P1, P5]. Based on the students' feedback, and published papers accepted by international journals, the Bond Graph is effective for force analysis in modeling and simulation [P1, P4]. In addition, the Lagrangian Bond Graph offers Mechatronics students a simple alternative method to traditional energy analysis for presenting the energy of spatial dynamics [P5]. The “Bond Graph benefits Mechatronics education method” theory was accepted by the Industrial Electronics Society (IES) and Student & Young Professionals Activity (S & YPA) [P5]. The detail is shown in Appendix B.

Publications

- P1: Guo, Z., Korondi, P., & Szemes, P. T. (2023). Bond-Graph-Based Approach to Teach PID and Sliding Mode Control in Mechatronics. *Machines*, 11(10), 959. doi.org/10.3390/machines11100959.
- P2: Fink, N., Zenan, G., Szemes, P., & Korondi, P. (2023). Comparison of Direct and Inverse Model-based Disturbance Observer for a Servo Drive System. *Acta Polytechnica Hungarica*, 20(4). [doi:10.3390/machines11100959](https://doi.org/10.3390/machines11100959).
- P3: G. Zenan, P. T. Szemes and P. Korondi, "Bond graph-based teaching method to enhance the synergy of mechatronics in Lab VIEW," 2022 IEEE 9th International Conference on e-Learning in Industrial Electronics (ICELIE), Brussel, Belgium, 2022, pp. 1-6. [doi:10.1109/ICELIE55228.2022.9969437](https://doi.org/10.1109/ICELIE55228.2022.9969437).
- P4: Zenan, G, and Péter Tamás SZEMES. "Hydraulic system with PID control under photovoltaic panel supply using LabVIEW." In 2020 3rd International Symposium on Small-scale Intelligent Manufacturing Systems (SIMS), pp. 1-6. IEEE, 2020. [doi:10.1109/SIMS49386.2020.9121415](https://doi.org/10.1109/SIMS49386.2020.9121415).
- P5: G. Zenan, H. A. Neamah and P. Tamás Szemes, "Bond Graph Benefits the Education in Mechatronics Engineering," 2024 IEEE 21st International Power Electronics and Motion Control Conference (PEMC), Pilsen, Czech Republic, 2024, pp. 1-6, [doi: 10.1109/PEMC61721.2024.10726329](https://doi.org/10.1109/PEMC61721.2024.10726329).

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Appendix

A Three-year Test Content and criteria

There are three questions in the test, each question needs to be solved by students using mathematics and the Bond Graph. The first question focuses on the description of the dynamics system. The second is about the electrical circuit and the third question focuses on the mechanical system or the multiple domain system.

The lecturer corrects each question, the lecturer should score both of the methods, Bond Graph and the mathematics.

The test results are the following: [Three years students mod and sim test results](#)

B List of S & YPA recipients for IEEE-PEMC 2024

The list of S&YPA recipients for IEEE-PEMC 2024

NAME	AFFILIATION	PAPER NO.	
LUIS FERNANDO GAONA	TECNOLOGICO NACIONAL DE MEXICO EN CELAYA	PEMC24-000008	ADOPTING OPC UA FOR EFFICIENT AND SECURE FIRMWARE TRANSMISSION IN INDUSTRY 4.0 SCENARIOS
ZENAN GUO	UNIVERSITY OF DEBRECEN	PEMC24-000079	BOND GRAPH BENEFITS THE EDUCATION IN MECHATRONICS ENGINEERING
SALMAN KHAN	TALLINN UNIVERSITY OF TECHNOLOGY	PEMC24-000108	RELIABILITY EVALUATION OF THE UNIVERSAL POWER ELECTRONIC INTERFACE CONVERTER FOR PV APPLICATIONS
SOURABH SINGH	TU DELFT	PEMC24-000053	END OF LIFE INFLUENCING FACTORS FOR DUAL ACTIVE BRIDGE COMPONENTS IN FLOW BATTERY APPLICATION
KOSUKE SHIKATA	KEIO UNIVERSITY	PEMC24-000063	HYBRID VELOCITY/FORCE FILTERED INTEGRAL PROPORTIONAL CONTROL FOR DAMPING OF TORSIONAL VIBRATION
ALON KUPERMAN	BEN GURION UNIVERSITY OF THE NEGEV	PEMC24-000028	EFFICIENCY OF PASSIVE MAGNETIC ENERGY HARVESTERS OPERATING UNDER HIGH PRIMARY CURRENTS

Figure 2. The list of SYPA recipients for IEEE-PEMC 2024

The figure is the list of S & YPA recipients for IEEE-PEMC 2024. The candidate was one of six selected from more than 130 contenders. The recipients are required to present their work separately based on their conference paper.

C Sample of Three-year Test Contents

Obai Mahfouz MW8KCF

SSCP

Long side folded, when submitted!

MK3MOD1R06R117-EN Modelling and Simulation Prototype Technologies I.

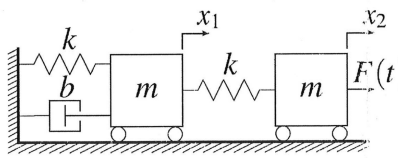
Grade offer test, time to solve: 60 minutes. 11th of December, 2019

Name (Capital): [REDACTED]

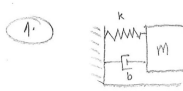
Neptun code (Capital): [REDACTED]

Important: Please note units for each parameter and state variable! Please do clean and readable work!

- 1 Degree-Of-Freedom, Spring(K)-Mass(M)-Dumper(D) system with PI type position control.
Solution: schematic, equation of motion in time domain, Bond Graph and Block diagram
2. Rectifier circuit with diode bridge, filter capacitor and load resistor. Consider the diode as an ideal switch (simplest nonlinear diode model).
Solution: electronics schematic, dynamic equation (input: AC voltage, output load resistor current), Bond Graph and block diagram.
3. Please do the modelling of following translational mechanical system:



Solution: dynamic equation (input: force, output: displacements), Bond Graph, block diagram, and state space model.

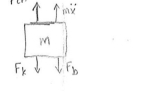


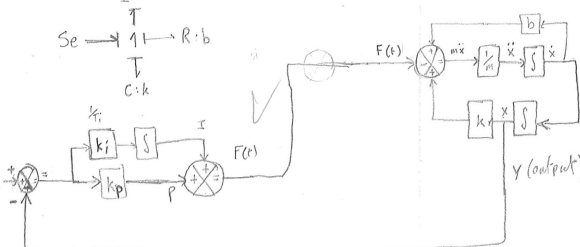
$F_k = k \cdot x$

$F_b = b \cdot \dot{x}$

$\dot{x} = \frac{b}{m} \dot{x} + \frac{k}{m} x - F(t)$

$m\ddot{x} = b\dot{x} + kx - F(t)$





y (output)

Figure 3. Test content in 2019

73%

Important: Please note units for each parameter and state variable! Please do clean and readable work!

Every task has to be written down on separate page. The number of the task must be on the top of every paper on the left side. Please use units for parameters and variables!

Please, write on every page, in the upper left corner with capital letters the followings: Name (same in Neptune), Neptune code, Date, "Mod. And Sim. I. Test", Task: X (X = task number),

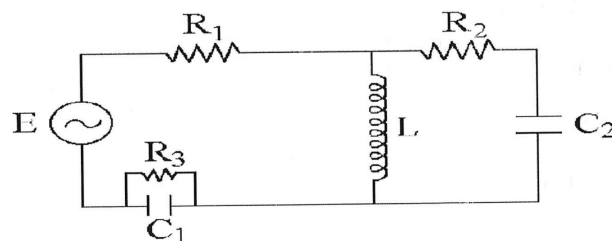
The student is responsible for the quality of his/her work! Unreadable matters will be cancelled!

Exercises:

1. 1 Degree-Of-Freedom, parallel connected, Spring(K)-Mass(M)-Dumper(D) system with PD type speed control. 24

Solution: schematic, plant state space in time domain, closed loop transfer function in frequency domain, Bond Graph and Block diagram

2. Please do the modelling of following electrical system: impedance Bond Graph and block diagram. 19



3. Please do the modelling of following rotational mechanical system: 30

Solution: dynamic equation in time domain (input: $e_{in}(t)$ input voltage,

state variables: angular displacement of DC motor $x_1(t)$ and angular velocity of DC motor $x_2(t)$; output: $y(t)$, angular displacement of the wheel)),

Bond Graph, block diagram, and state space model.

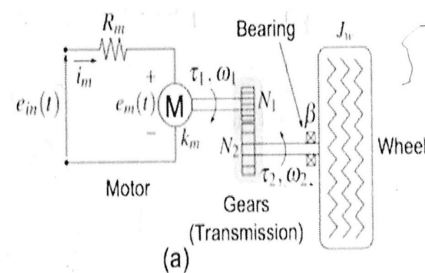


Figure 4. Test content in 2021

Important: Please note units for each parameter and state variable! Please do clean and readable work!

Every task must be written down on separate page. The number of the task must be on the top of every paper on the left side. Please use units for parameters and variables!

Please, write on every page, in the upper left corner with capital letters the followings: Name (same in Neptune), Neptune code, Date, "Mod. And Sim. I. Test", Task: X (X = task number),

The student is responsible for the quality of his/her work! Unreadable matters will be cancelled!

Exercises:

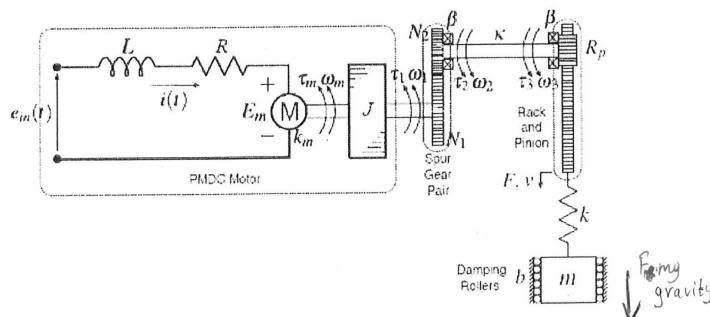
1. 1 Degree-Of-Freedom, parallel connected, Spring(K)-Mass(M)-Dumper(D) system with PI type position control.

Solution: schematic, plant equation of motion in time domain, plant transfer function in frequency domain, plant Bond Graph, closed control loop block diagram, input-output transfer function

2. Parallel connected Resistor-Capacitor-Inductor, with AC voltage excitation ($v_{in}(t)$).

Solution: electronics schematic, state space model in time domain: (input: AC voltage ($v_{in}(t)$), state variable: current ($i(t)$), output: resistor voltage $v_R(t)$), Bond Graph and block diagram.

3. Please do the modelling of following translational mechanical system:



Solution: dynamic equation in time domain (input: $v_{in}(t)$, output: displacement of mass ($y(t)$), Bond Graph, block diagram, and state space model in time domain.

Figure 5. Test content in 2022