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Option: **Control Engineering**

Title:

Design and Implementation of 3-DOF Helicopter Bench Test System

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Abstract

The scope of this project is to control the speed and the direction of dc motor using H-bridge and PWM and developing a mathematical model for the motor. It is asked to develop a 3-DOF (3 Degree Of Freedom) helicopter for laboratory experiment which is often used in control research education and analysis for the design and implementation of linear and non-linear control concepts. It is composed by three rotational joints, with the end bar carrying a pair of propellers actuated by DC motors. Measurements of the joints angles are supplied by incremental encoders. Two speed controllers based on H-bridges drivers for actuating the DC motor/propeller assemblies. Both angular measurements and control voltages provided by PC based hardware interfaces and software LABVIEW programs.

Based on the identified model, a PID controller has been developed to control the speed of the motor. The simulation results show that the designed control system can guarantee high precision altitude and a good control under multi operation points.

Key-words: H-bridge, PWM, 3-DOF helicopter, encoder, LABVIEW, PID

Dedication

This work is dedicated to every individual who helped me walk through my path to succeed in this educational and academic journey, which was a long one filled with hard work and perseverance, the task wasn't easy like everything in life because success wasn't meant to be that way and for that sacrifices were to be made and struggles were to be endured, I would like thank my parents who took a major part in this course, even though thank you isn't enough to repay their favour for the reason that they gave everything they could to make the thing as easy as possible for me, I also want to express my deepest gratitude to the lovely people I met at my trainings who provided me all the knowledge they could. Finally, I would like send my greatest love to my brothers, friends and family members who were also a source for my aspirations ambitions.

Sayeh Meddour yasser / Belghait Naim

Acknowledgement

We would like to thank a number of people who have contributed to the result in many different ways. First of all we pay our obeisance to Allah, the almighty to have best owed upon us good health, courage and inspiration. After Allah, we express our sincere and deepest gratitude to our supervisor, Dr.ouadi abderrahmane for guidance and help during the project. His expertise, invaluable guidance, constant encouragement, understanding, patience and criticism added considerably to our experience.Without his continual inspiration, it would have not been possible to complete this study. We would like to express our gratitude to all IGEE teachers and staff for their kindness and great help they provide to us to do this modest work.

Finally, we must express our very profound gratitude to our parents and family for providing us with unfailing support and continuous encouragement throughout our years of study and through the process of researching and writing this report. This accomplishment would not have been possible without them. Thank you.

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List of Abbreviations & Acronyms

3-DOF	3 degree of freedom
DAQ	Data Acquisition
DC	Direct Current
EMF	Electromotive Force
I/O	Input Output
KVL	Kirchhoff's Voltage law
MIMO	Multiple input multiple output
PD	Proportional Derivative
PI	Proportional Integral
PID	Proportional Integral Derivative
PPR	Pulse per revolution
PWM	Pulse Width Modulation
RPM	Revolution Per Minute
SISO	Single input single output

General introduction

Recently, considerable attention has been attracted to the analysis and control of helicopters due to their real military and civil applications as well as scientific significance. The 3-DOF Helicopter experiment provides a top model used for transport search and rescue missions. It can be used to understand and develop control laws for a vehicle that has dynamics representative of a dual rotor rig body helicopter or any device with similar dynamics. Moreover, this helicopter comprising many of the challenges because it is not only actuated using the propellers, but it also contains multi-body dynamics. It is composed by three rotational joints, with the end bar carrying a pair of propellers actuated by DC motors. Measurements of the joints angles are supplied by incremental encoders and two speed controllers based on H-bridges drivers for actuating the DC motor/propeller assemblies. Both angular measurements and control voltages provided by PC based hardware interfaces and software LABVIEW programs.

The helicopter has severe nonlinearities and open-loop unstable dynamics as well as significant cross-coupling between their control channels which make the control of such multiple-input multiple-output (MIMO) systems a challenging task. Based on the obtained linear models, classical single input single-output (SISO) techniques with a PID controller are widely used like (Reiner et al, 1995). Of course, this approach will require multi-loop controllers, which makes their design inflexible and difficult to tune. Hence, the MIMO controller design approaches have received more and more attention. For example, successful implementation of LQR design for a helicopter system has been presented in (Apkarian, 1998) [1].

In the beginning of writing this report numerous reports on the Quanser helicopter and similar problems have been read and studied to get an understanding on how an already established helicopter rig behaves and what problems might come up during the project. Many have already succeeded to build such a helicopter rig which is being used in control engineering courses at universities all over the world. The Quanser helicopter has also been used in several theses where candidates develop different mathematical models and evaluate the performance of different control strategies [1].

There are Many approaches dealing especially with modeling and control of the 3-DOF Quanser helicopter, have been recently proposed [12]. But they have based just for the mathematical model of the helicopter without control strategy. In addition, most of the models that have been developed previously in literature have made several assumptions in the modeling process neglecting some parameters such as friction parameters, the axis orientation of various joints, air drag and the motors/propellers dynamics.

This report is organized as follows. First starting by the H bridge and PWM to control the speed and the direction of DC motor, followed by the modeling of the motor. A model for a three degree of freedom (3-DOF) helicopter is explained using free-body diagram. The mathematical model is developed and then linearized. A system description of the applied controller (PI or PID) is shown, and a position control was made using incremental encoder then the results are presented to illustrate the effectiveness of the proposed control algorithm. Finally, conclusions are drawn in the last section.

CHAPTER 1:

3-DOF Helicopter System Description

1.1 3-DOF Helicopter system description

The 3-DOF helicopter consists of a base upon which a long arm is mounted. The arm carries the “helicopter body” on one end and a counterweight on the other such that the effective mass of the helicopter is light enough for it to be lifted using the thrust from the motors. The helicopter frame is suspended from an instrumented joint mounted at the end of the long arm and is free to pitch about its center. The arm is installed on an additional 2-DOF instrumented joint which allows the helicopter arm to tilt about an “elevation” axis as well as swivel about a vertical (travel) axis. Two DC motors are mounted at each end of a rectangular frame and drive two propellers. These two DC motors can generate a force proportional to the current passing through the DC motors. The force generated by the propellers causes the helicopter body to lift off the ground. The motors axes are parallel and the thrust vector is normal to the frame [12].

A positive voltage applied to the front motor causes a positive pitch while a positive voltage applied to the back motor causes a negative pitch. A positive voltage to either motor also causes an elevation of the body. If the body pitches, the thrust vectors result in a travel of the body as well. Rotary encoders mounted on these axes allow for measuring the elevation and travel of the arm. The pitch angle is measured via a third encoder [14].

The 3-DOF Helicopter plant is depicted in Figure 1.1

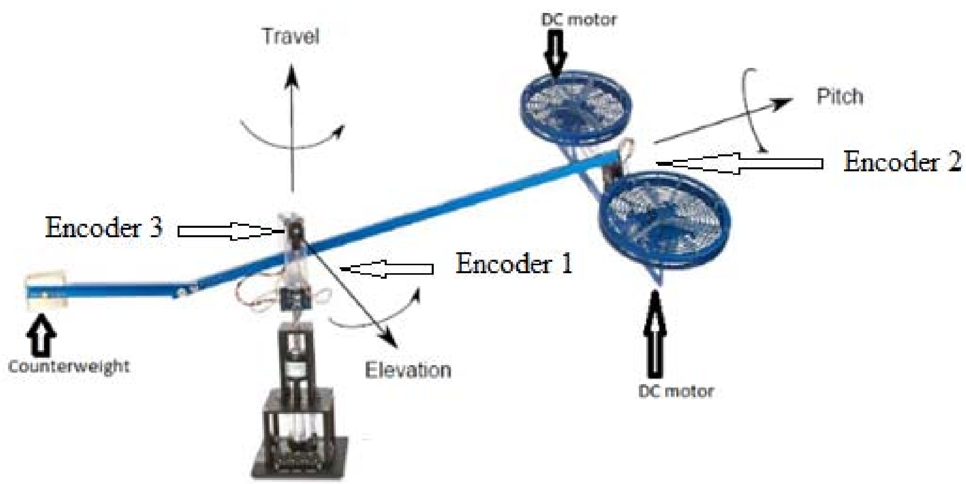


Figure 1.1 3-DOF Helicopter construction.

1.1.1 Coordinate Systems

Pitch Angle

The angle which the helicopter is rotated around the axis running through the pitch joint.

• Positive **ρ** if the front rotor goes down (the front motor is labeled on the helicopter).

• Defined as zero when the helicopter is horizontal.

• Negative **ρ** if the front rotor goes up.

Elevation Angle

The angle between the global XY-plane and the arm.

•Defined as zero when the arm is horizontal.

• Negative **ϵ** if the helicopter is below the joint.

• Positive **ϵ** if the helicopter is above the joint of the elevation axis.

Travel Angle

The angle which the rig is rotated around the global Z-axis.

• Positive τ if rotating in the right-hand sense (as depicted in Figure 1.2).

• Zero $\boldsymbol{\tau}$ at starting point.

• Negative $\boldsymbol{\tau}$ if rotating in the left-hand sense.

Distances

All geometric distances will be labeled with L and are measured in meters, the distances in Figure 1.2 are defined as:

• $\mathbf{L_W}$: The distance between the elevation axis and the center of gravity of the counter-weight.

• $\mathbf{L_M}$: The distance between the elevation axis and the helicopter.

• $\mathbf{L_H}$: The distance between the pitch axis and the center of the propellers.

• $\mathbf{L_\rho}$: The distance between the pitch axis and the helicopter center of gravity.

Masses

The masses are defined as:

• $\mathbf{m_W}$**:** The mass of the counterweight**.**

• $\mathbf{m_h}$**:** The mass of the helicopter (including motors).

Furthermore, the forces F_F and F_B represent the thrust generated by the front and the back motor respectively.

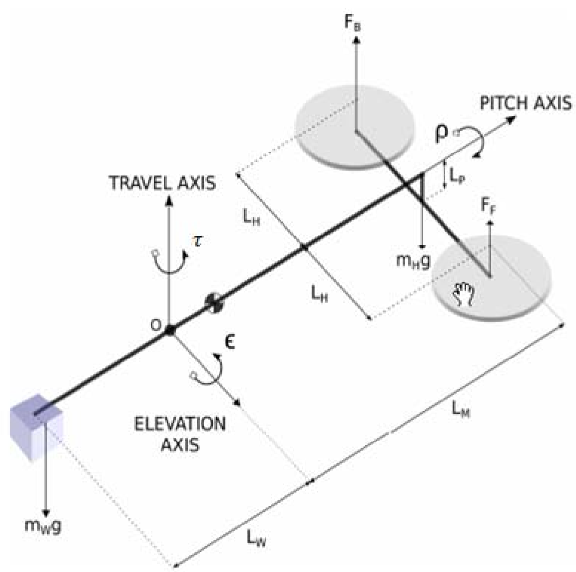
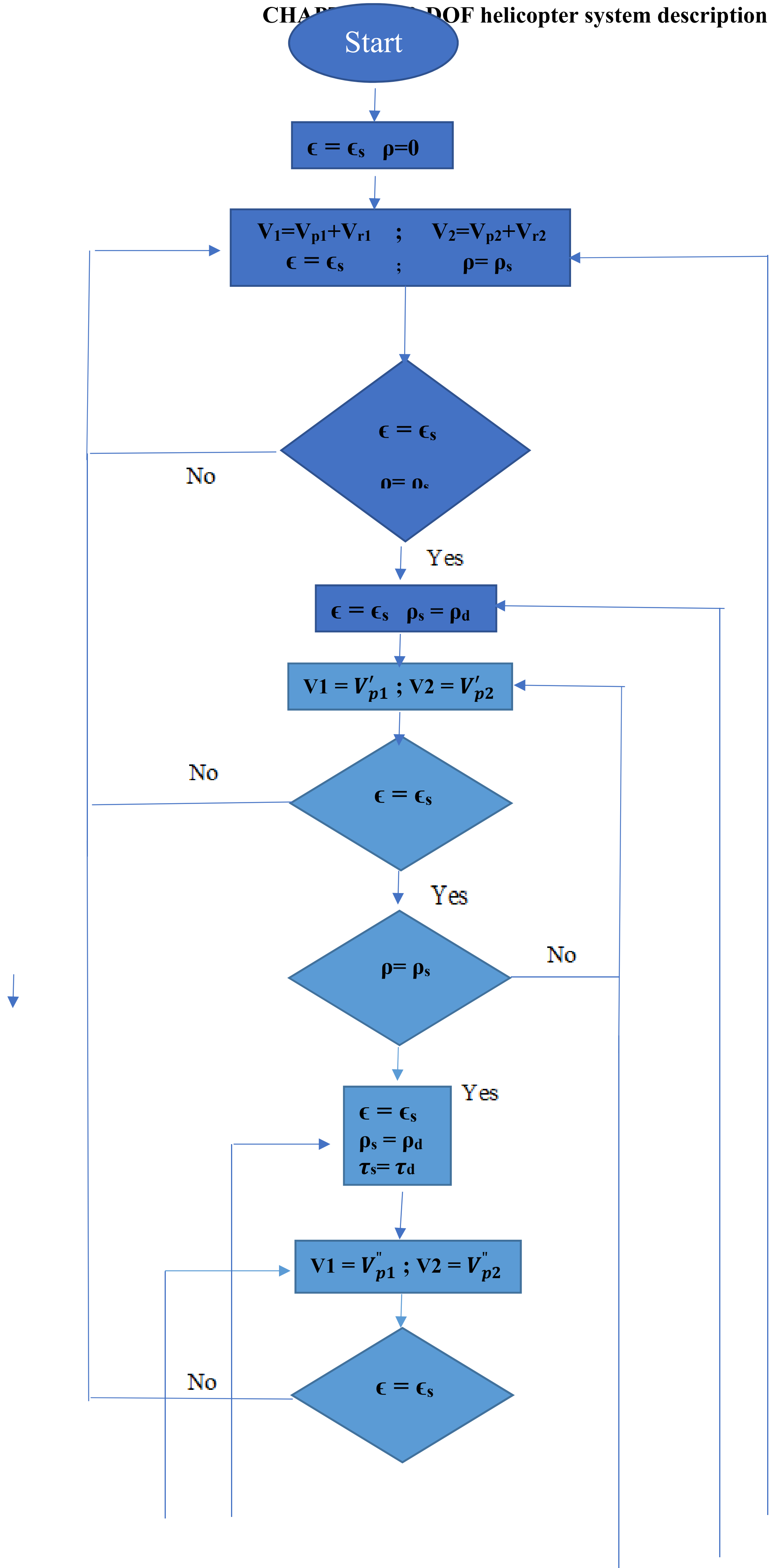
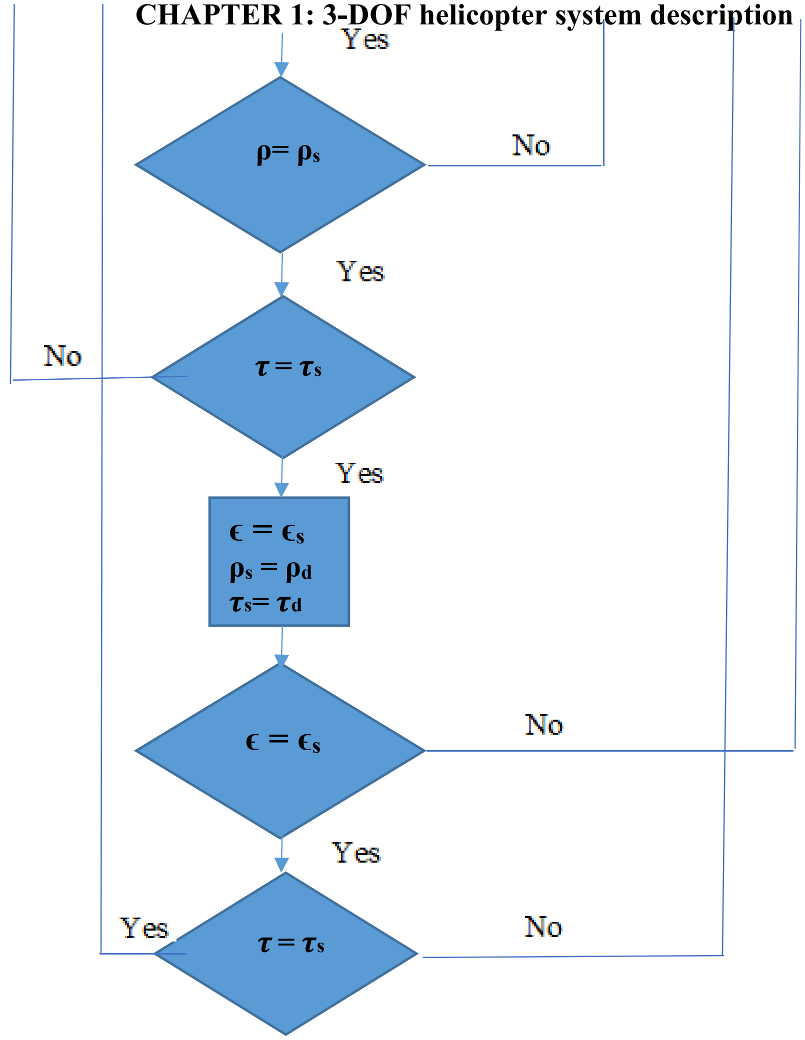


Figure 1.2 Free-body diagram of 3-DOF Helicopter [11].

1.1.2 Algorithm and flowchart

The 3-DOF helicopter motion is driven by the two motors voltages v1 and v2. We first start by setting the elevation angle and initializing the pitch angle at zero. Then we set each motor voltage which is equal to the addition of the position voltage Vp and the reference voltage Vr, to get the appropriate elevation and pitch angles, we check the encoders readings and repeat till we get to the set angles ρ_s and ϵ_s. To pitch the helicopter, we set ϵ to ϵ_s and ρ_s to the desired pitch angle ρ_d. After setting V1 to V'_{p1} and V2 to V'_{p2} we read ϵ, if it is equal to the set elevation angle we continue to the rest of the program, else we go back setting the appropriate voltages. Then we read the pitch angle, if it is equal to the set angle we continue, else we set V1 to V'_{p1} and V2 to V'_{p2}. To drive the helicopter in travel mode we set ϵ to ϵ_s , ρ to the desired ρ_d and τ_s the travel angle to the desired travel angle τ_d. We first check if ϵ is at the set position, if it doesn't, we return to supply the appropriate voltages. Finally, we read the travel angle encoder, if it is equal to τ_s we loop to set the elevation angle, ρ_s to ρ_d and τs to τd. If τ doesn't equal to the desired travel angle we recalibrate ρ to the desired pitch angle.


Start
ϵ = ϵs ρ=0
V1=Vp1+Vr1 ; V2=Vp2+Vr2
ϵ = ϵs ; ρ= ρs
ϵ = ϵs
No
Yes
ϵ = ϵs ρs = ρd
V1 = V′p1 ; V2 = V′p2
No
ϵ = ϵs
Yes
ρ= ρs
No
Yes
ϵ = ϵs
ρs = ρd
τs= τd
V1 = V"p1 ; V2 = V"p2
No
ϵ = ϵs


Yes
ρ= ρs
No
Yes
No
τ = τs
Yes
ϵ = ϵs
ρs = ρd
τs= τd
ϵ = ϵs
No
Yes
Yes
τ = τs
No

1.2. DC Motor

Almost every mechanical movement that we see around us is accomplished by an electric motor. Electric machines are used in energy conversion. Motors take electrical energy and produce mechanical energy. Electric motors are broadly classified into two different categories: DC (Direct Current) and AC (Alternating Current). Within these categories are numerous types, each offering unique abilities that suit their specific applications. There are different kinds of DC motors, but they all work on the same principles. In this part, we will take a look at their basic principle of operation and their characteristics. It's important to understand motor characteristics so we can choose the right one for our application requirement which is three degree of freedom helicopter (3-DOF).

1.2.1. DC motor Construction

The DC motor has two basic parts: the rotating part that is called the armature and the stationary part that includes coils of wire called the field coils. The stationary part is also called the stator. The armature is made of coils of wire wrapped around the core, and the core has an extended shaft that rotates on bearings. We should also notice that the ends of each coil of wire on the armature are terminated at one end of the armature. The termination points are called the commutator, and this is where the brushes make electrical contact to bring electrical current from the stationary part to the rotating part of the machine. The coils that are mounted inside the stator are called field coils and they may be connected in series or parallel with each other to create changes of torque in the motor.

Stator

- The *stator* is the stationary outside part of a motor.
- The stator of a permanent magnet dc motor is composed of two or more permanent magnet pole pieces.
- The magnetic field can alternatively be created by an *electromagnet*. In this case, a DC coil (field winding) is wound around a magnetic material that forms part of the stator.

Rotor

- The *rotor* is the inner part which rotates.
- The rotor is composed of windings (called armature windings) which are connected to the external circuit through a mechanical commutator.
- Both stator and rotor are made of ferromagnetic materials. The two are separated by air-gap.

Armature winding

A winding is made up of series or parallel connection of coils.

- Armature winding - The winding through which the voltage is applied or induced.
- Field winding - The winding through which a current is passed to produce flux (for the electromagnet).
- Windings are usually made of copper [2].

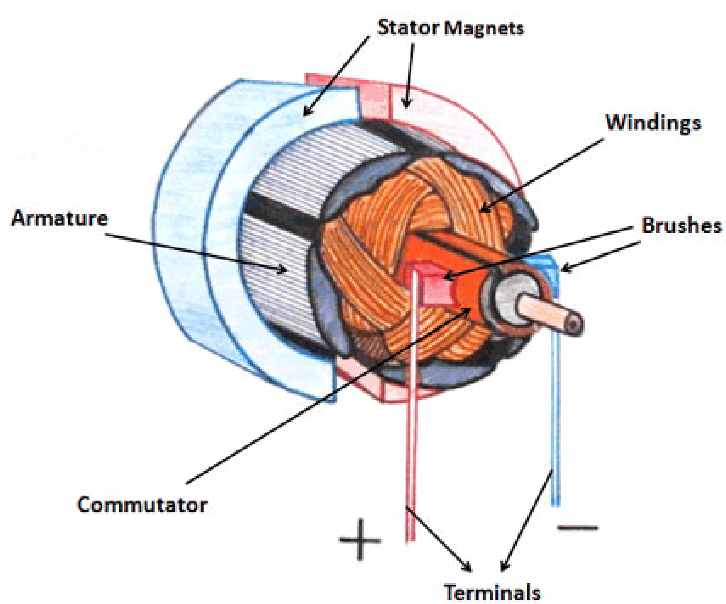


Figure 1.3 Construction of DC Motor.

1.3. Tacho-generator

An electromechanical generator is a device capable of producing electrical power from mechanical energy, usually the turning of a shaft. When not connected to a load resistance, generators will generate voltage roughly proportional to the shaft speed. With precise construction and design, generators can be built to produce very precise voltages for certain ranges of shaft speeds, thus making them well-suited as measurement devices for shaft speed in mechanical equipment. A generator specially designed and constructed for this use is called a *tacho-meter* or *tacho-generator*. Often, the word "tach" (pronounced "tack") is used rather than the whole word.

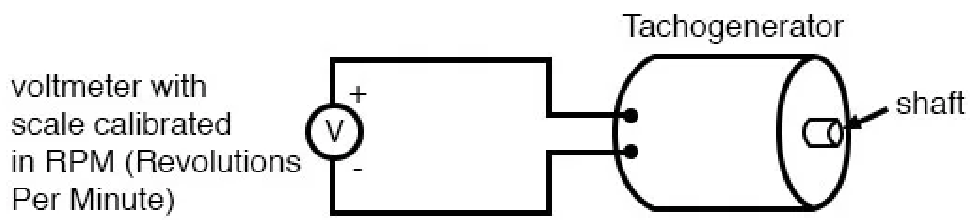


Figure 1.4 Tacho-generator working principle.

By measuring the voltage produced by a tacho-generator, you can easily determine the rotational speed of whatever it is mechanically attached to. One of the more common voltage signal ranges used with tacho-generators is 0 to 10 volts. Obviously, since a tacho-generator cannot produce a voltage when it's not turning, the zero cannot be "live" in this signal standard. Tacho-generators can be purchased with different "full-scale" (10 volts) speeds for different applications. Although a voltage divider could theoretically be used with a tacho-generator to extend the measurable speed range in the 0-10 volt scale, it is not advisable to significantly over speed a precision instrument like this, or its life will be shortened.

Tacho-generators can also indicate the direction of rotation by the polarity of the output voltage. When a permanent-magnet style DC generator's rotational direction is reversed, the polarity of its output voltage will switch. In measurement and control systems where directional indication is needed, tacho-generators provide an easy way to determine that.

Tacho-generators are frequently used to measure the speeds of electric motors, engines, and the equipment they power: conveyor belts, machine tools, mixers, fans, etc[3].

The DC tacho-generator is a small DC generator. The armature is driven by motor shaft whose speed is feedback. The rotor iron cored and field is a permanent magnet. The armature of a DC tacho-generator is of similar to design to that of conventional DC motor. These generators are normally provided with more than two poles for a smooth output.

When the rotor is stationary, there is no relative motion between the magnetic field and the winding, the output voltage is zero. As the rotor speed increases, the relative motion between the magnetic field and the winding also increases, hence the output voltage induced in the winding.

1.4. PWM (Pulse Width Modulation)

There are different techniques available for the speed control of DC motors. The phase control method is widely adopted in which AC to DC converters are used to supply the DC motors, but has certain limitations mainly it generates harmonics on the power line and it also has a poor power factor. when operated at lower speeds. The second method is PWM technique, which has got better advantages over the phase control. In our proposed project, the uses of PWM is needed in order to control the speed of DC motor.

1.4.1. PWM principles:

Pulse width modulation control works by switching the power supplied to the motor on and off very rapidly. The DC voltage is converted to a square wave signal, alternating between a full scale of nearly 12 v and 0 v, giving the motor a series of power “kicks”.

Pulse width modulation technique (PWM) is a technique for speed control which can overcome the problem of poor starting performance of a motor.

PWM for motor speed control works in a very similar way. Instead of supplying a varying voltage to a motor (voltage amplifier), it is supplied with a fixed voltage value (such as 12v) which starts it spinning immediately. The voltage is then removed and the motor coasts. By continuing this voltage on/off cycle with a varying duty cycle, the motor speed can be controlled.

The duty cycle therefore describes a fraction of the cycle for which the square wave is in the logic 1 state. When multiplying this value by 100, it gives the duty cycle value in terms of a percentage.

Duty Cycle = (t / T) × 100.

For example, if the period (T) of the signal was 2 seconds, and the duration of the logic 1 state (t) was 1 second, then the following expression gives the duty cycle in percentage. **(1 / 2) × 100 = 50 %.**

The wave forms in the below Figure to explain the way with which this method of control operates. In each case the signal has maximum and minimum voltages of 12v and 0v.

- In wave form, the signal has a mark space ratio of 1:1 with the signal at 12v for 50% of the time, the average voltage is 6v, so the motor runs at half its maximum speed.
- In wave form, the signal has mark space ratio of 3:1 which means that the output is at 12v for 75% of the time. This clearly gives an average output voltage of 9v, so the motor runs at 3/ 4 of its maximum speed.
- In wave form, the signal has mark space ratio is 1:3 giving an output signal that is 12v for just 25% of the time. The average output voltage of this signal is just 3v, so the motor runs at 1/4 of its maximum speed [4].

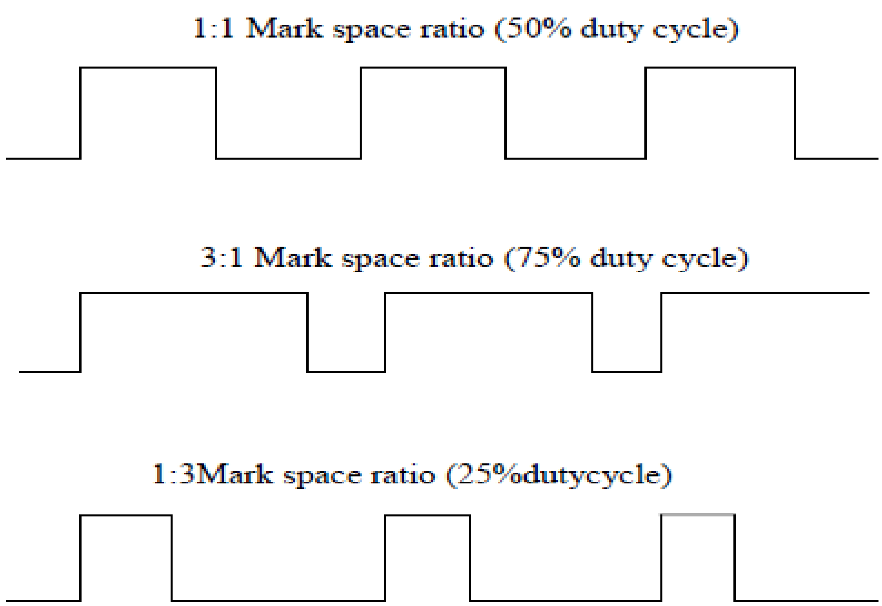


Figure 1.5 Pulse Width Modulation Waveform.

1.4.2 PWM generator techniques

The PWM signals can be generated in a number of ways. there are several methods:

- DC method.
- Digital method.
- Discret IC.

DC method:

A block diagram from DC to PWM generator is shown below

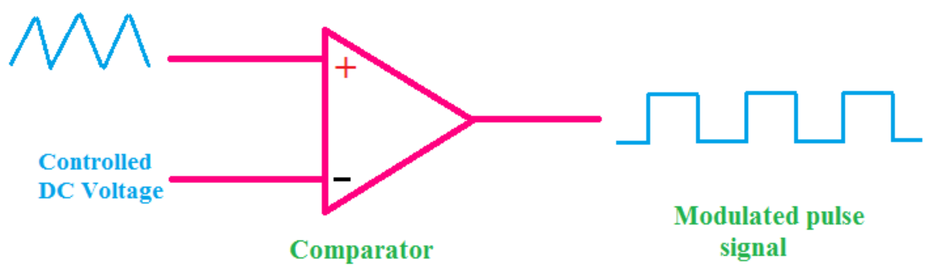


Figure 1.6 Generation of PWM signal.

Digital Method

The digital method involves incrementing a counter and comparing its value with a pre-loaded register value, or value set by an ADC. They normally use a counter that increments periodically and is reset at the end very period of the PWM. When the counter value is more than the reference value, the PWM output will change state from high to low.

PWM generator chips

There are several IC's available which converts a DC level into a PWM output. Many of these are designed for use in switched mode power supplies. Unfortunately, the devices designed for switch mode power supplies not to allow the mark-space ratio to alter over the entire 0 – 100% range. Many limits the maximum to 90% which is effectively limiting the power one can send to the motors [4].

1.5. H-bridge

The H-bridge is probably one of the most commonly used type of bi-directional DC motor control circuits. The direction in which a motor rotates is determined by which side of the motor is connected to the positive and negative terminals. Swapping the positive and negative terminals will cause the motor to rotate in the opposite direction. An H-Bridge is used to control the direction of the motor and to also provide enough current for the motor to run.

1.5.1 H-Bridge configuration

The h-bridge configuration is a common way to change the direction of the power supply. The H-bridge circuit is so named because the basic configuration of the four switches, either electromechanical relays or transistors resembles that of the letter "H" with the motor positioned on the center bar. Using two pairs of switches that need to be switched together. The switch pairs are diagonally opposite to each other. Each pair of switches need to be closed at the same time. So, on the diagrams below S1 and S4 form one pair and S2 and S3 the other pair. H-bridge in it's off position is shown bellow.

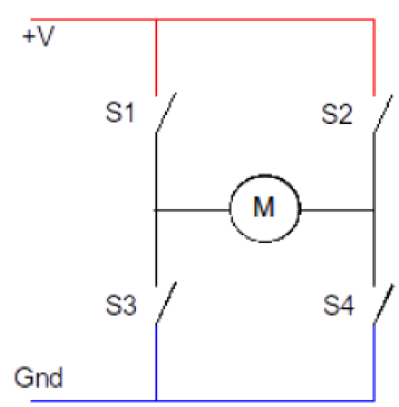


Figure 1.7 H-bridge in off position.

When S1 and S4 are closed the positive supply goes to the left of the motor and the negative to the right. The motor will then work in one direction clockwise direction.

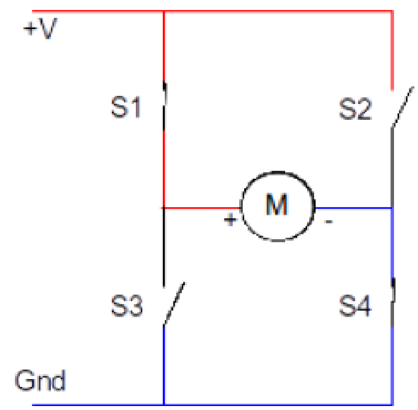


Figure 1.8 H-bridge clockwise direction.

To change the direction switches S1 and S4 need to be opened and then S2 and S3 closed. The positive supply is now provided to the right of the motor and the negative to the left, so the motor will now turn into the opposite direction counter clockwise direction [5].

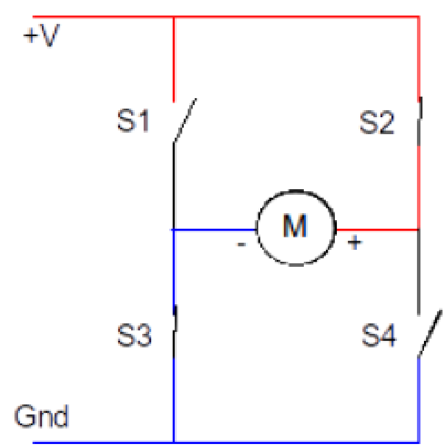


Figure 1.9 H-bridge counter clockwise direction.

Note that if S1 and S3 are open at the same time, the DC voltage will short and you will have very high current and rapid heating of the MOSFETs. This also occurs if S2 and S4 are open at the same time. Be sure to never let this situation occur!

1.5.2 H-Bridge truth table

Table1.1 H-bridge input table.

IN2	IN1	Function
0	0	Coast
0	1	Clockwise
1	0	Counter clockwise
1	1	Break

Table1.2 H-bridge output table.

Function	Q1	Q2	Q3	Q4
Coast	0	0	0	0
Clockwise	1	0	0	1
Counter clockwise	0	1	1	0
Brake	1	1	0	0

Table1.3 H-bridge full combinatorial logic full truth table.

IN2	IN1	Q1	Q2	Q3	Q4	Function
0	0	0	0	0	0	Coast
0	1	1	0	0	1	Clockwise
1	0	0	1	1	0	Counter Clockwise
1	1	1	1	0	0	Brake

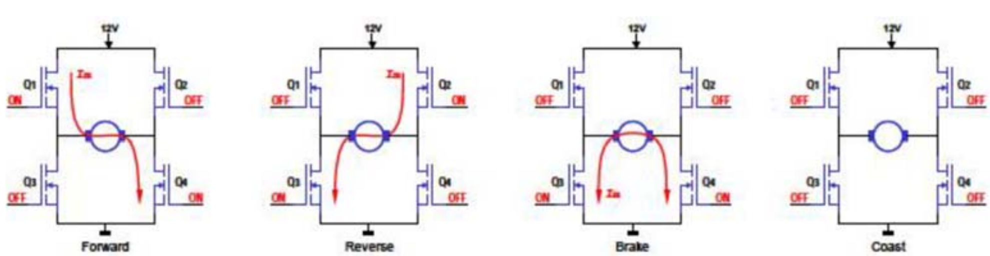


Figure 1.10 Bi-directional rotation using a full-bridge [5].

1.6. Rotary incremental encoder

A rotary encoder is a type of position sensor which is used for determining the angular position of a rotating shaft. It generates an electrical signal, either analog or digital, according to the rotational movement. There are many different types of rotary encoders which are classified by either Output Signal or Sensing Technology. The particular rotary encoder that we will use is an incremental rotary encoder. Incremental rotary encoders are used in machines and installations in different resolutions. Thanks to their simple design, they are more economical to manufacture than absolute rotary encoders. On the other hand, they only indicate position changes and cannot detect movements without a power supply.

1.6.1 Features

- This type of encoder outputs a pulse train(set) in response to the amount of rotational displacement of the shaft. A separate counter counts the number of output pulses to determine the amount of rotation based on the count.
- To detect the amount of rotation from a certain input shaft position, the count in the counter is reset at the reference position and the number of pulses from that position is added cumulatively by the counter. For this reason, the reference position can be selected as desired, and the count for the amount of rotation can be unlimited.
- the phase-Z signal, which is generated once a revolution, can be used as the origin within a revolution.

1.6.2 Structure

A magnetic encoder consists of a rotating gear made of ferrous metal and a magnetic pick-up that contains a permanent magnet and the sensing element. The gear, which is mounted on the rotating shaft, has precisely machined teeth that provide the code pattern. As the disk rotates, these teeth disturb the magnetic flux emitted by the permanent magnet, causing the flux field to expand and collapse. These changes in the field are sensed by the sensing element, which generates a corresponding digital or pulse signal output.

Two kinds of magnetic pick-ups exist:

- **Hall effect** -- pick-ups use a semiconducting sensing element that relies on the Hall effect to generate a pulse for every gear tooth that passes the pickup.
- **Variable reluctance** -- pick-ups use a simple coil of wire in the magnetic field. As the gear teeth pass by the pick-up and disturb the flux, they cause a change in the reluctance of the gear/magnet system. This induces a voltage pulse in the sensing coil that is proportional to the rate flux change [6].

  This structure is shown in Figure 1.11

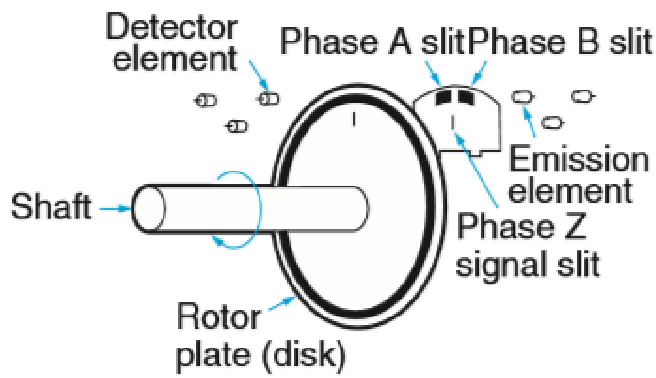


Figure 1.11 Structure of rotary incremental encoder.

When the disk will start rotating step by step, the phases A and B will start making contact with the common pin and the two square wave output signals will be generated accordingly. Any of the two outputs can be used for determining the rotated position if we just count the pulses of the signal. However, if we want to determine the rotation direction as well, we need to consider both signals at the same time [7].

CHAPTER 2:

H-bridge DC Motor Implementation, Controller and Modeling

2.1. DC Motor Modeling

2.1.1 Theoretical part

A common actuator in mechanical control systems is the DC motor. It directly provides rotary motion. For example, in our Project we need to control the two DC motor of 3-DOF helicopter. The motor modeling equations are based on references [8],[9], [10]. The electric circuit of the armature and the free body diagram of the rotor are shown in the following Figure 2.1 including the armature resistance R_a and winding leakage inductance L_a.

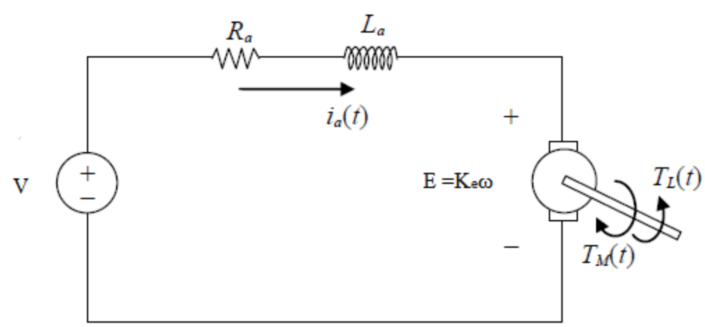


Figure 2.1 Electric circuit of the armature.

The parameters of the DC motor are listed and described in the table below.

Table 2.1 DC motor parameters.

Parameter	Definition	Comment
K_e	The back-emf	Dominate factor in determining motor's steady state speed fora given voltage
K_t	Torque Constant	Determines the motor required current for a given torque output
R_a	Terminal Resistance	Determines how much power will be dissipated in the motor fora given current level
L_a	Armature Inductance	Determines how fast current to the motor can be turned on
J	Moment of inertia of the rotor	A measure of an object's resistance to changes in its rotation rate
B	Viscous (Damping) Friction	A measure of dynamic friction

ω	Angular velocity	A measure of speed due to the angle

The motor torque T is related to the armature current i_a by a constant factor K_t. The back-emf E is related to the rotational velocity by the constant factor K_e as illustrated in the following equations:

$$T_M = K_t i_a \quad (2.1)$$

$$E = K_e \omega \quad (2.2)$$

According to Kirchhoff's voltage law, the electrical equation of the DC motor is described as:

$$V = R_a i_a + L_a \frac{di_a}{dt} + K_e\, \omega \quad (2.3)$$

If the input voltage V is constant, the resulted armature current $i_a(t)=I_a$, the angular velocity $\omega\,(t)=\Omega$ and the torque $T_M(t)=T$ are also constants in the steady state. From (2.1) to (2.3), we have

$$R_a I_a + K_e \Omega = V \quad (2.4)$$

Under the conservation of power, it is known that the input power $I_a V$ is equal to the external power T Ω and the power consumed in the resistance is $R_a I_a^2$

$$R_a I_a^2 + T\Omega = VI_a \quad (2.5)$$

Substituting V into (2-5) yields

$$T_M = K_e I_a \quad (2.6)$$

From (2.5) and (2.6), knowing that both K_t and K_e are the same where $K=K_t= K_e$, the DC motor is used to drive an external torque $T_f(t)$ of payload then its mechanical behavior is described as

$$J \frac{d\omega(t)}{dt} + B\, \omega(t) = T_M(t) - T_f(t) \quad (2.7)$$

Where J is the rotor moment of inertia and B is the frictional coefficient.

So:

$$K_t i_a = J \frac{d\omega(t)}{dt} + B\, \omega(t) + T_f \quad (2.8)$$

Note that the electrical time constant L_a/R_a is often neglected since it is at least one order in magnitude smaller than the mechanical time constant J/B. In other words, by neglecting the term $\frac{di_a}{dt}$ so (2.3) becomes

$$i_a(t) = (1/R_a)V - (K/ R_a)\, \omega(t) \quad (2.9)$$

Substituting it into (2.8), we get:

$$\frac{d\omega(t)}{dt} + \left(\frac{B}{J} + \frac{K^2}{R_a}\right)\omega(t) = -\frac{1}{J} T_f(t) + \frac{K}{J\,R_a} V \qquad (2.10)$$

Clearly, the motor will encounter two external sources, the input voltage V to drive the motor and the torque $T_f(t)$ reacted from the payload.

In the state-space form, the equations above can be expressed by choosing the rotational speed and electric current as the state variables and the voltage as an input. The output is chosen to be the rotational speed or current, so by representing equations (2.3) and (2.8) in a state space model form provides:

$$\begin{bmatrix} \dot{i_a} \\ \dot{\omega} \end{bmatrix} = \begin{bmatrix} \frac{-R_a}{L_a} & \frac{-K_e}{L_a} \\ \frac{K_t}{J} & \frac{-B}{J} \end{bmatrix} \begin{bmatrix} i_a \\ \omega \end{bmatrix} + \begin{bmatrix} \frac{1}{L_a} & 0 \\ 0 & \frac{-1}{J} \end{bmatrix} \begin{bmatrix} V \\ T_f \end{bmatrix} \qquad (2.11)$$

So, the system matrices are:

$$A = \begin{bmatrix} \frac{-R_a}{L_a} & \frac{-K_e}{L_a} \\ \frac{K_t}{J} & \frac{-B}{J} \end{bmatrix} \quad ; \quad B = \begin{bmatrix} \frac{1}{L_a} & 0 \\ 0 & \frac{-1}{J} \end{bmatrix} \quad ; \quad C = [0 \quad 1]$$

Using Laplace Transform, the above modeling equations can be expressed in terms of s. The armature current can be expressed using Laplace Transform as follows:

$$I_a(s) = \left[\frac{1}{L_a s + R_a}\right][V(s) - K_e\,\omega(s)]$$

(2.12)

Rotational speed also expressed as following:

$$W(s) = \left[\frac{1}{Js + B}\right][K_t I_a(s) - T_f] \qquad (2.13)$$

Therefore, the transfer function can be directly expressed as follows:

$$\frac{W(s)}{V(s)} = \frac{K_t}{s(JsR_a + BR_a + K_t K_e)} \qquad (2.14)$$

In most conditions, the relevant influence for the inductance is inappreciable contrast and the mechanical motion can be ignored. It is obvious that in this condition the influence for the back emf is difficult to distinguish by virtue of the friction, and the transfer function can be expressed as:

$$\frac{W(s)}{V(s)} = \frac{K_t/R_a}{Js^2+(B+\frac{K_tK_e}{R_a})s} = \frac{K}{s(\tau s+1)} [rad/s] \quad (2.15)$$

Where

- $K = \frac{K_t}{BR_a+K_tK_e}$ [rad/Vs]
- $\tau = \frac{R_a J}{BR_a+K_tK_e}$ [s]

In the other hand, for the case of operation without any payload $T_f(t)=0$, the state equation can be rewritten as:

$$\dot{x(t)} = Ax(t) + Bu(t).$$

$$y(t) = Cx(t).$$

Where

$$A=\begin{bmatrix} \frac{-R_a}{L_a} & \frac{-K_e}{L_a} & 0 \\ \frac{K_t}{J} & \frac{-B}{J} & 0 \\ 0 & 1 & 0 \end{bmatrix} \quad ; \quad B=\begin{bmatrix} \frac{1}{L_a} & 0 \\ 0 & \frac{-1}{J} \\ 0 & 0 \end{bmatrix} \quad ; \quad C=[0 \quad 0 \quad 1]$$

The SIMULINK model of the DC motor with its parameters is expressed as follow in Figure 2.2.

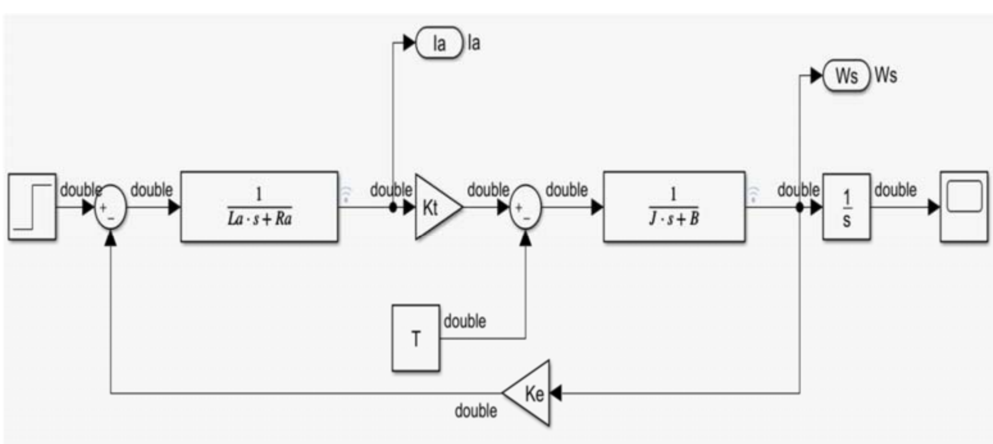


Figure 2.2: Simulink model of the DC Motor.

2.1.2 Practical part

In this project we need to control the two DC motors, speed and direction control using PWM and H-bridge respectively. Both of the PWM and the H-bridge circuits have been designed in Proteus software in order to control the two motor of the 3-DOF helicopter. A system identification of the combined system (PWM, H-bridge and the DC motor) is required for speed control design.

2.1.2.1. PWM implementation

Motors as a class require very high currents to operate. Being able to vary their speed with PWM technique which increases the efficiency of the total system by quite a bit, without forgetting that the PWM is more effective in controlling motor speeds at low RPM than linear methods. Different types of PWM techniques are available. The high frequency carrier-wave is compared with the sinusoidal modulating signals to generate the appropriate gating signals for the inverters. The other PWM techniques are evolved from this basic PWM techniques. In proteus software we have tried to design a simple circuit that can guarantee high precision altitude and good results.

The designed PWM circuit is shown below in Figure 2.3.

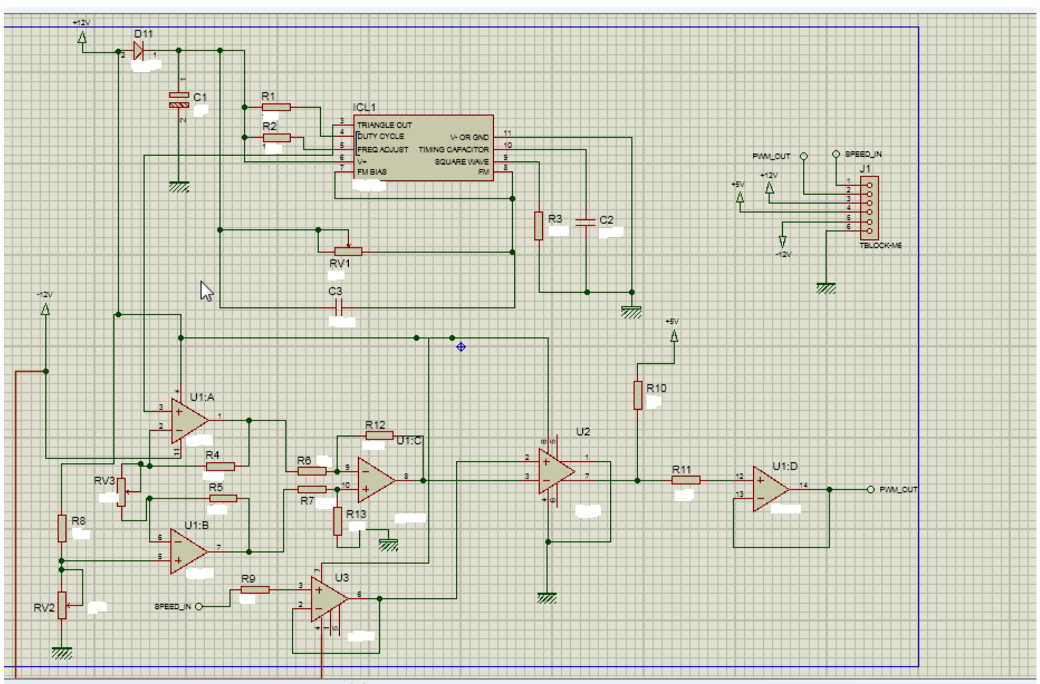


Figure 2.3 PWM circuit in proteus software.

As mentioned previously Pulse-width modulation (PWM) is used for controlling the digital signal by varying the width of the "on" phase or duty cycle. The duty cycle is expressed as the percentage of being fully (100%) on. When the wave form signal has 50% of the time in each period, the average voltage is the half, so the motor runs at half of its maximum speed. Hence, we can control the speed of the dc motor using duty cycle percentage. Here is a Figure that illustrates some cases:

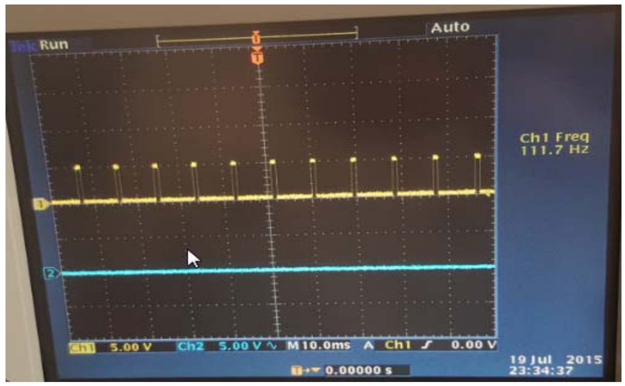


Figure 2.4 PWM output with duty cycle of 10%

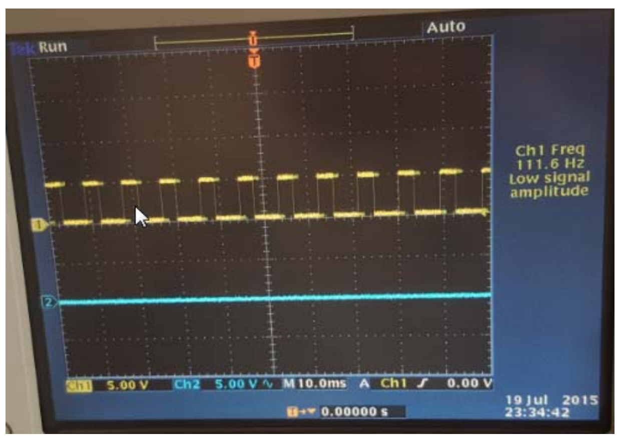


Figure 2.5 PWM output with duty cycle of 50%.

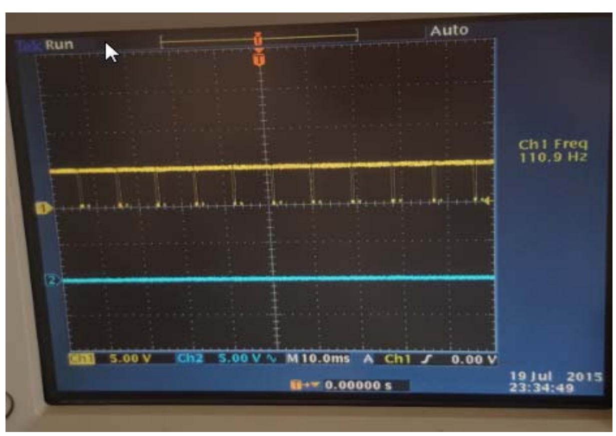


Figure 2.6 PWM output with duty cycle of 95%.

Now we talk about the hardware part. In order to make the helicopter more practical by trying to reduce the weight and reduces the circuit size. We have implemented the interface of PWM circuit shown in Figure 2.7 from Proteus software into printed circuit board shown in Figure 2.8.

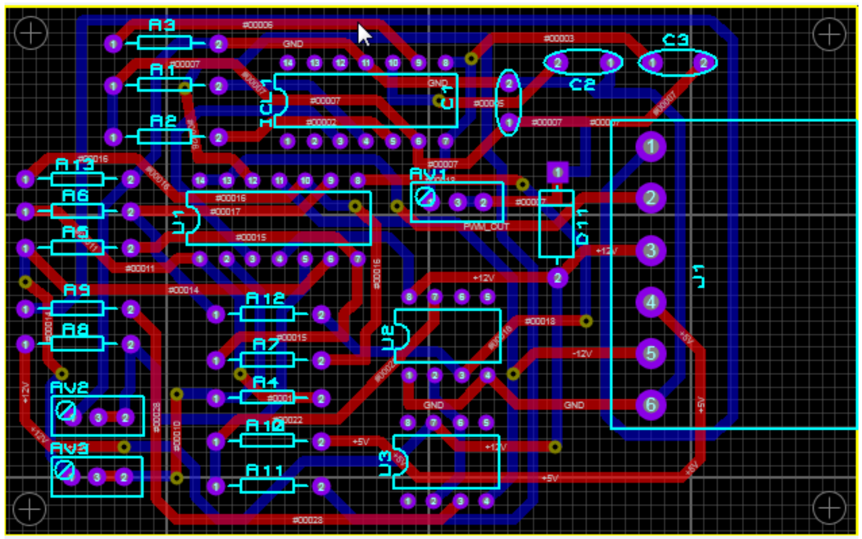


Figure 2.7 PWM PCB layout in proteus software.

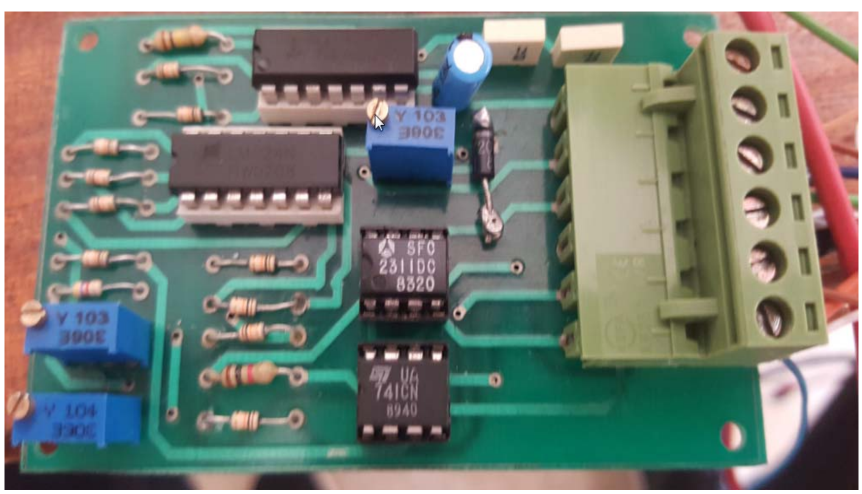


Figure 2.8 PWM printed circuit board.

2.1.2.2. H-bridge implementation

H-bridges are available as integrated circuits, or can be built from discrete components. We have designed an H-bridge circuit that have all the control and power stages in one package, so it can control the DC motor in Off/Forwards/Backwards/Brake states. The designed H-bridge circuit is shown in Figure 2.9.

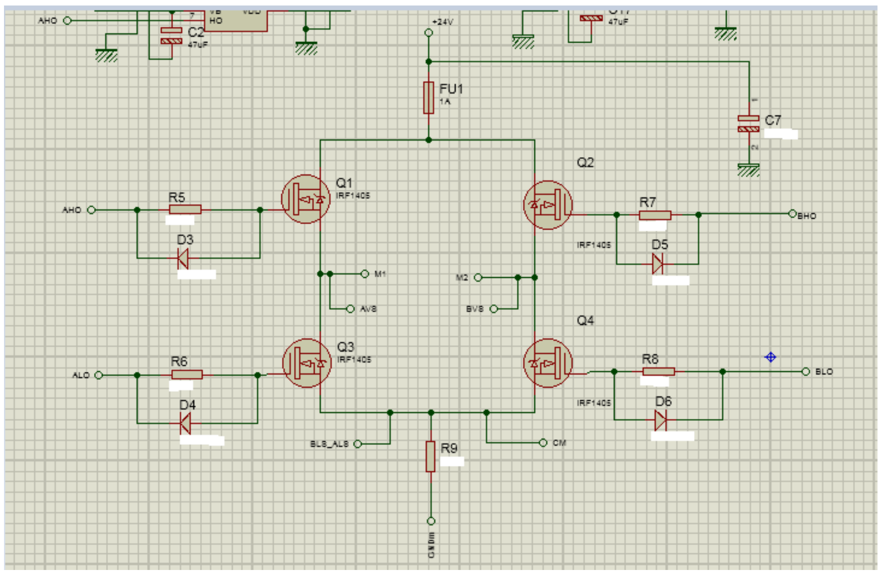


Figure 2.9 H-bridge designed circuit.

The brake state is an extra state that allows to do a fast brake of the motor by shorting its terminals. Our brake circuit is shown bellow in Figure 2.10.

The designed H-bridge circuit has all what we have discussed before. It can also provide an enough current to run more than one motor at the same time with maximum current which is about 10 A.

The H-bridge circuit is designed in proteus software and the interface of the circuit shown in Figure 2-10 is converted into printed circuit board shown in Figure 2-11.

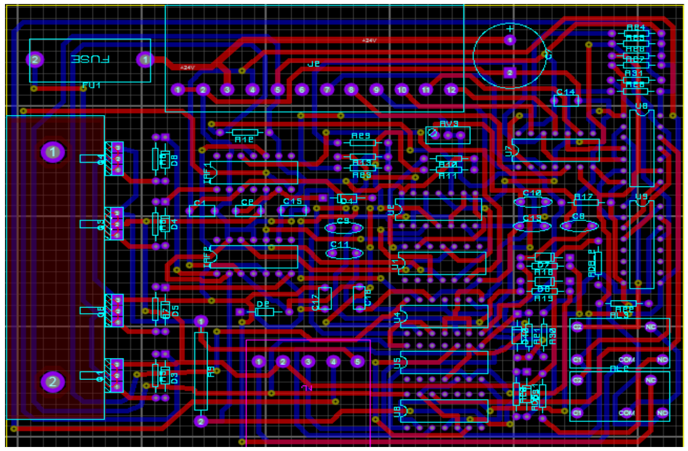


Figure 2.10 H-bridge printed circuit board layout in proteus software.

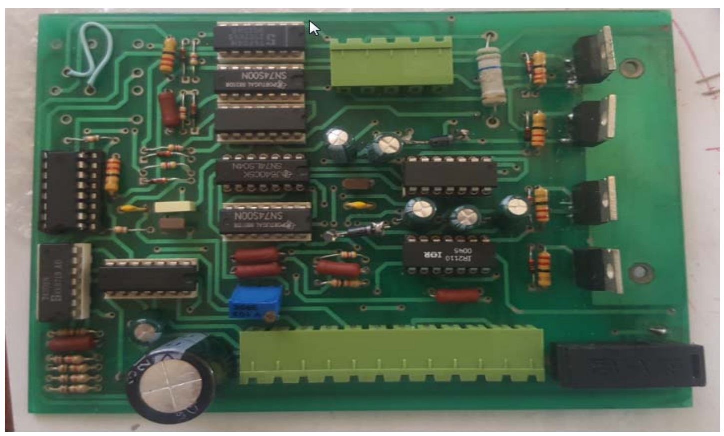


Figure 2.11 H-bridge printed circuit board.

The construction of PWM and H-bridge is done, the tacho-generator output voltage responses are shown in the Figure 2.12.

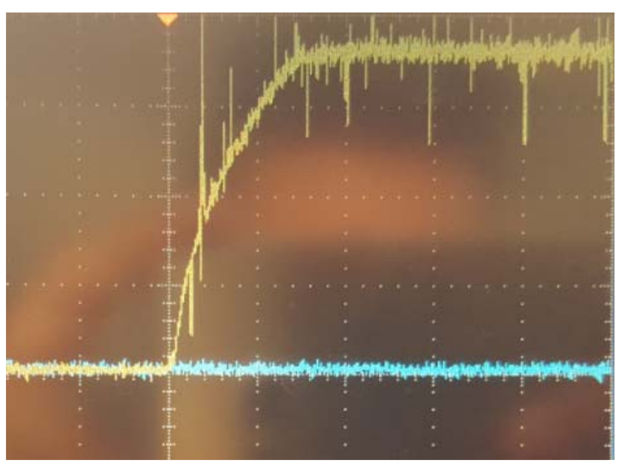


Figure 2.12 The output response of the DC motor.

2.2 System identification

As we have seen in equation (2.15) the DC motor model is described as a first order system because of its small armature inductance so the effect of the factor "s^2" is negligible and the system described as a first order system.

First order models with a time delay are used in a large number of different applications, where the main dynamic is reasonable damped. One of the most used methods for estimation of parameters in stable first order systems is to apply a step response. Based on the step response, it is easy to determine the gain, the time constant and the time delay as the equation (2.16).

$$G(s) = \frac{K}{Ts+1} e^{-\tau s} \qquad (2.16)$$

Its response is shown in Figure 2.13 and 2.14.

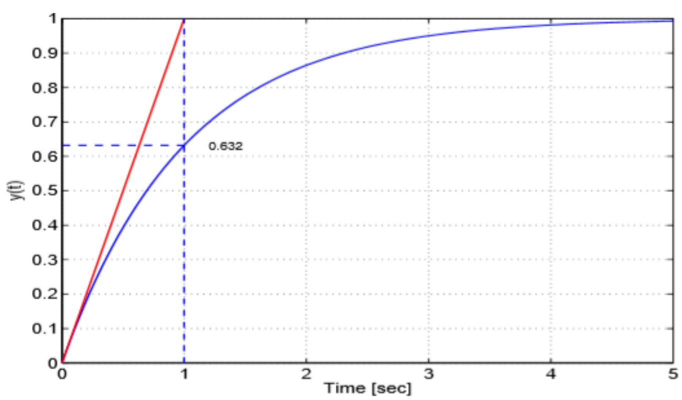


Figure 2.13 Step response for first order system without delay.

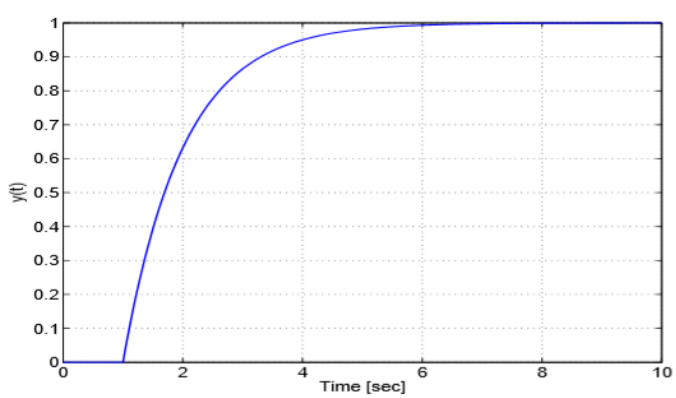


Figure 2.14 Step response for first order system with delay.

2.2.1 Procedure of identification

Table 2.2 The identification parameters.

Parameters	Description
Δu	The difference between the final and the initial value of the step response
Δy	The difference between the final and the initial value of the output response
y_{ss}	The steady state value of the output response
τ	The time delay between the step and the output

- Extract { Δu, Δy, y_{ss}, τ, $t_{0.63}$ }.
- Compute:

$$k = \frac{\Delta y}{\Delta u} \quad ; \quad T = t_{0.63} - \tau$$

We have designed a circuit of step response between zero and three volts, then we have connected it to the PWM input as shown in Figure 2.15.

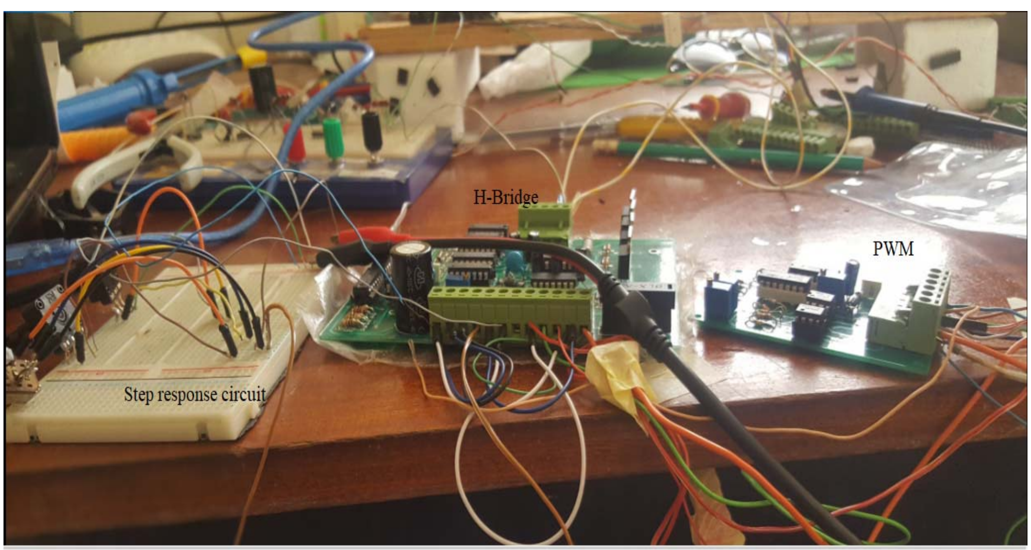


Figure 2.15 Whole circuit combinations.

The system that we need to identify it is shown bellow in figure 2.16

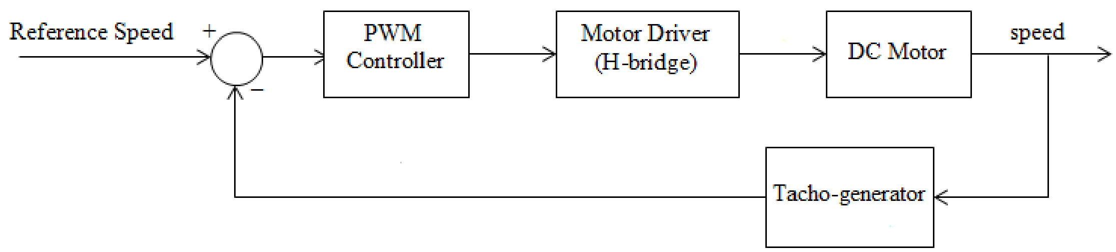


Figure 2.16 DC motor speed controller system.

The previous implemented circuit gives the output response illustrated in Figure 2.17.

Figure 2.17 Step and output response.

The steady state value of the system and the step input might not be known exactly because the disturbance might be included as well as other issues that might affect the steady state value like noise as we can see in Figure 2.17. After this, we need straight lines to extract precise data in the procedure of determining the parameters Δu, Δy, y_{ss}, τ and $t_{0.63}$. As shown bellow in Figure 2.18.

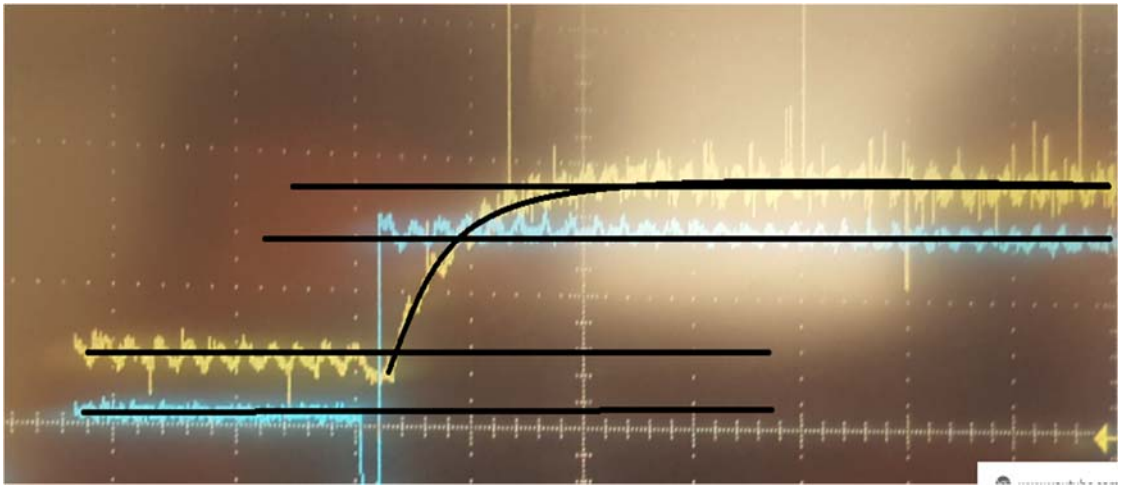


Figure 2.18 The clear waveform of output response.

From the Figure 2.18 we see that there is no delay so $\tau = 0$. Now we calculate the gain k and the time T.

$$\begin{cases} u1 = 0.2\ V \\ u2 = 2.9\ V \end{cases} \rightarrow \Delta u = 2.9 - 0.2 = 2.7\ \text{V}$$

$$\begin{cases} y1 = 1\ V \\ y2 = 3.6\ V \end{cases} \rightarrow \Delta y = 3.6 - 1 = 2.6\ \text{V}$$

We know that $k = \frac{\Delta y}{\Delta u}$ $\rightarrow$ $k = \frac{2.6}{2.7} = 0.96$

And $T = t_{0.63} - \tau \rightarrow T = t_{0.63} = 0.1\ s$

So, the transfer function of the system is expressed as follows:

$$G(s) = \frac{0.96}{0.1s+1} \qquad (2.17).$$

CHAPTER 3:

DC Motor Speed Controller and Position Measurement Using LABVIEW

3.1 PID controller

The PID controller is the most known and used controller in Control Design. It consists of proportional part, Integrator part and derivative part, as shown in Figure 3.1, in some applications we can use only two of them (e.g. PI controller, PD controller) it depends on the system to be controlled and the desired behavior.

The proportional part is defined as constant gain, Kp, the larger this constant gain is the faster is the system, but if we get too greedy and try to increase it more we may end up with unstable system.

The integral part consists of integrator and constant gain, Ki, this part of the controller has its effect on the steady state; the integrator is responsible of eliminating the steady state error of the system, but the smaller the steady state error is the larger the overshoot becomes.

The derivative part is consisted of derivation and constant gain, Kd, it has effect on the transient state, it helps to minimize the overshoot in the system.

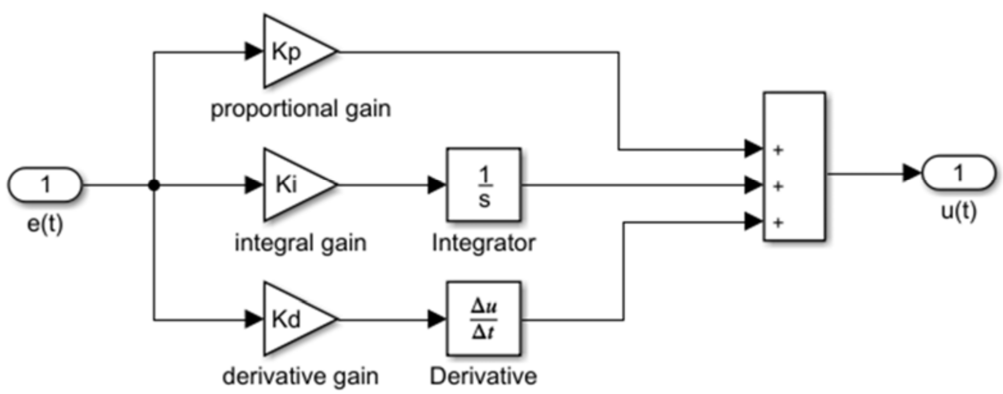


Figure 3.1 Conventional PID circuit**.**

The general and basic formula of PID controller is:

$$H(s) = Kp + Ki * \frac{1}{s} + Kd * s \qquad (3.12)$$

3.1.1 MATLAB estimation of PID parameters

After the identification of the system we have designed a PID controller using SIMULINK PID tuner to build a robust PID controller linked with the transfer function of our system and configure the step response between zero and six volts. Then we give initial values for our PID controller, before obtaining optimized ones as illustrated in Figure 4.2.

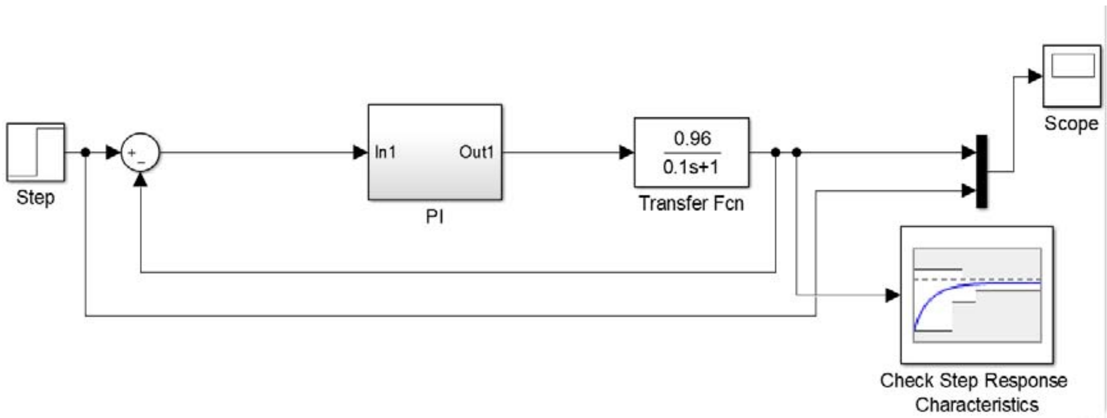


Figure 3.2 Feedback PID controller circuit**.**

For the optimization of controller values, we will use check step response characteristics block from SIMULINK library, and set our desired criterion as follow:

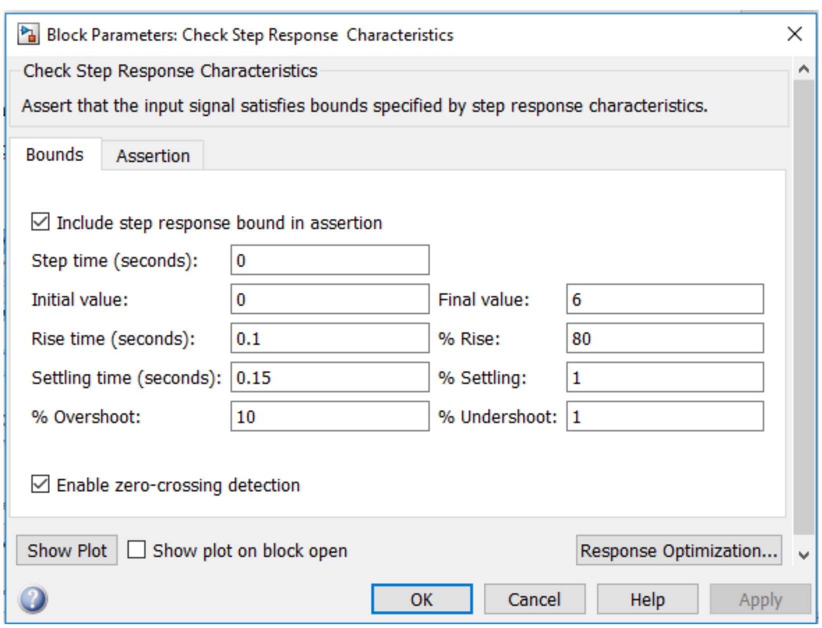


Figure 3.3 Criterion optimization**.**

The result of this procedure is shown in the following figures, this PID will be implemented to control the real system and see if it works correctly.

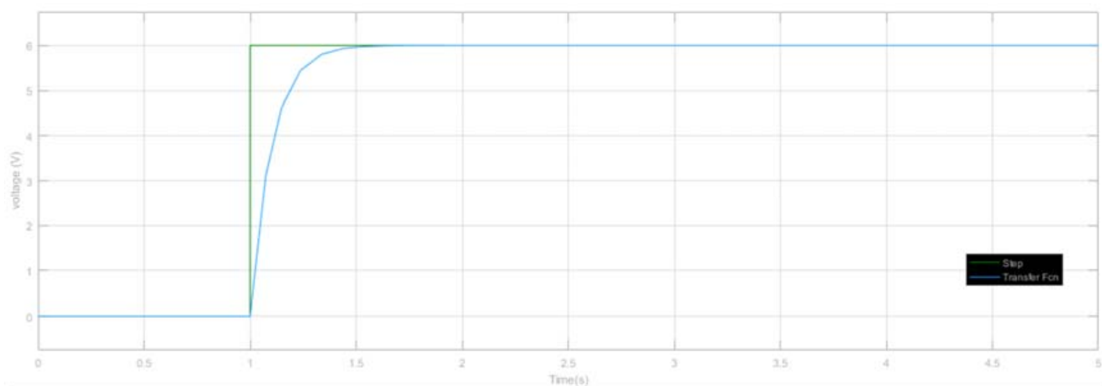


Figure 3.4 Optimized response.

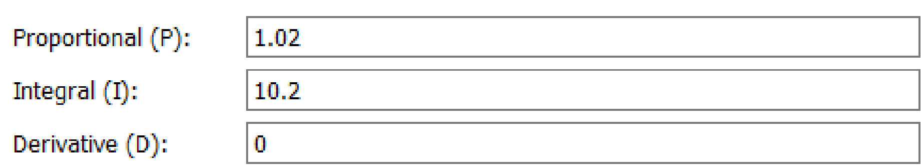


Figure 3.5 Optimized parameters.

After doing more iteration we have getting two PI and Two PID controllers:

- PI :

  Kc= 1.02 Kc= 1.02

  Ki= 0.098 Ki=0.0845

- PID :

  Kc= 1.068 Kc= 1.458

  Ki= 0.001 Ki=0.0043

  Kd=0.0843 Kd=0.0874

3.1.2 PID controller test using LABVIEW

After getting the parameters of our controller from the previous section, we determine the relationship between the tacho-geneator output voltage (volt) and the speed of the DC motor in rpm is measured using a tacho-meter (DT-2236). The experiment procedure is based on varying the motor supply voltage for varying the motor speed and measure it's the actual speed (rpm). A set of measurement data is recorded in table 3.1. Figure.3.6 gives the experimental relation between the tacho-generatot output voltage versus motor speed.

Table 3.1 Recorded values of voltages and speed.

Voltage (V)	Speed (rpm)
0.4	220
0.8	460
1.2	774
2	1540
3.2	2500
4	3125
5	3845
6	4600 max

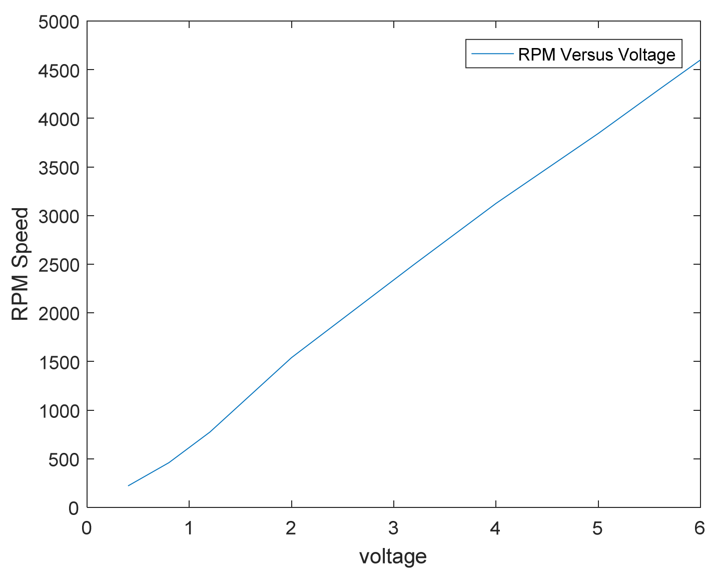


Figure 3.6 Speed vs tacho-voltage.

As we can see in Figure 3.6 we observe that the relationship between the speed and the tacho-generator voltage is linearly proportional by a factor of 800 so:

$$\textbf{speed} = \textbf{800} * \textbf{voltage} \quad (3.13)$$

The motor speed can now be calculated, by measuring the tach-generator output voltage. A closed loop speed control system can be developed using a PC based data acquisition board (NI USB 6009 see the appendix) and LABVIEW program. The DAQ board is used to acquire data, as motor speed, by means of tacho-generator voltage measurement. Then, a PI controller calculates the required dc voltage to output for controlling the PWM generator. This voltage is generated by the NI USB board for adjusting PWM signal, thus controlling the motor speed.

As we see in the Figure 3.7, we have used the relationship (3.13). The collection of data is used in rpm block. This block calculates the rpm mean value to get good results and avoid noise (implementation of low pass filter).

This filtered measured rpm speed is used as input to the PID controller block function. A range of 0 to 4600 rpm is used as a parameter, including the designed PID parameters values required for this PID controller block. The output value of this controller is converted to the required output voltage considered as an output process variable. The PID controller block diagram is illustrated in Figure 3.8.

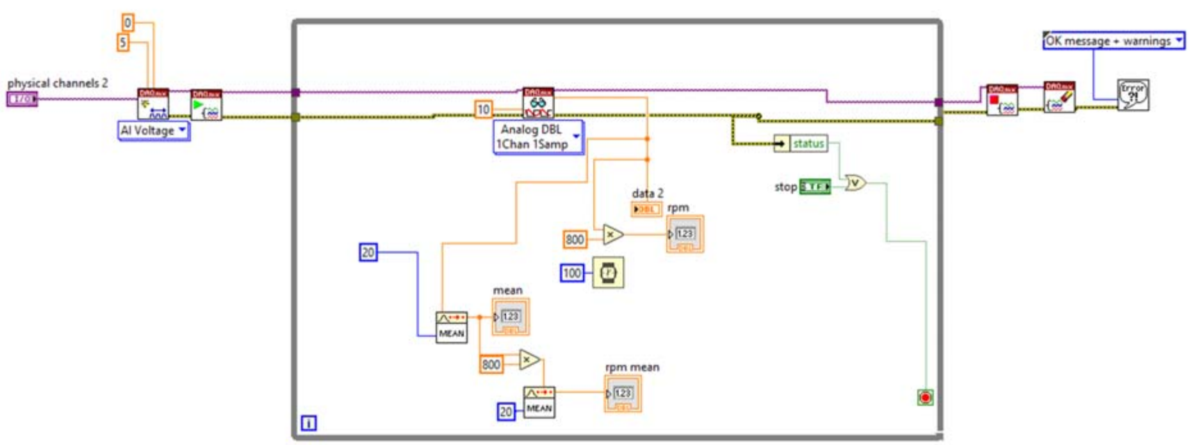


Figure 3.7 Data acquisition block diagram.

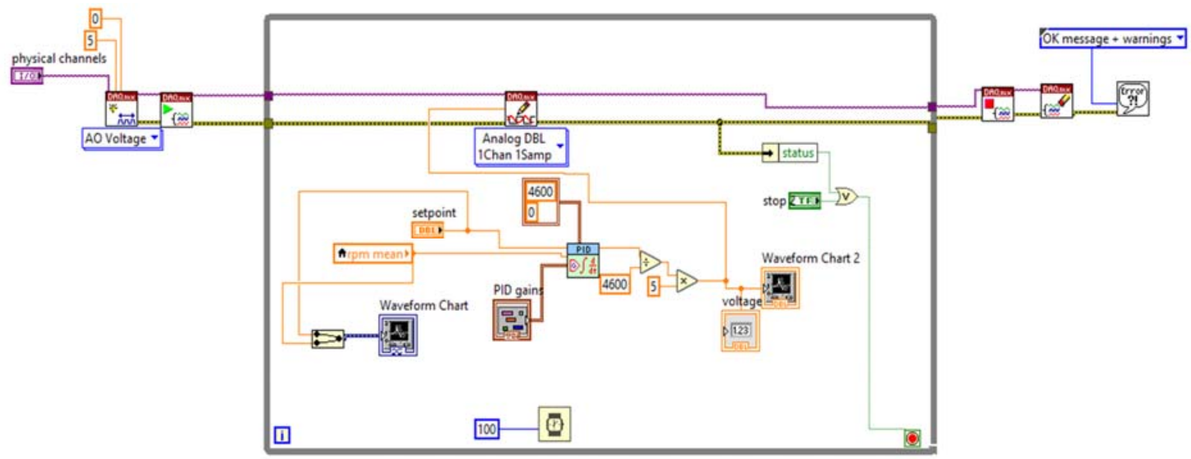


Figure 3.8 PID controller block diagram.

In the speed control we have used two types of controllers PI and PID using the previous parameters gotten from SIMULINK estimation. The result of our simulations is shown in Figures 3.9,3.10 and 3.12.

- For the first PI controller experiment, we have used the parameters Kc= 1.02 and Ki = 0.098. Figure 3.9 shows a desired speed profile to output motor speed response

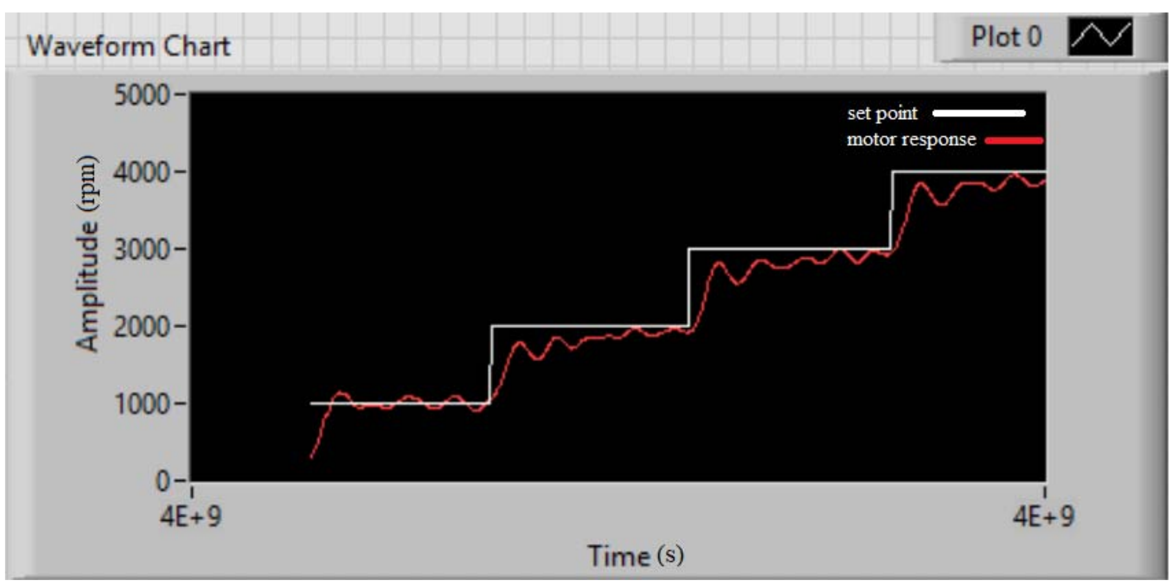


Figure 3.9 First PI controller result.

- For the second PI controller we have used the parameters Kc= 1.068, Ki = 0.0845. Figure 3.10 shows a desired speed profile to output motor speed response.

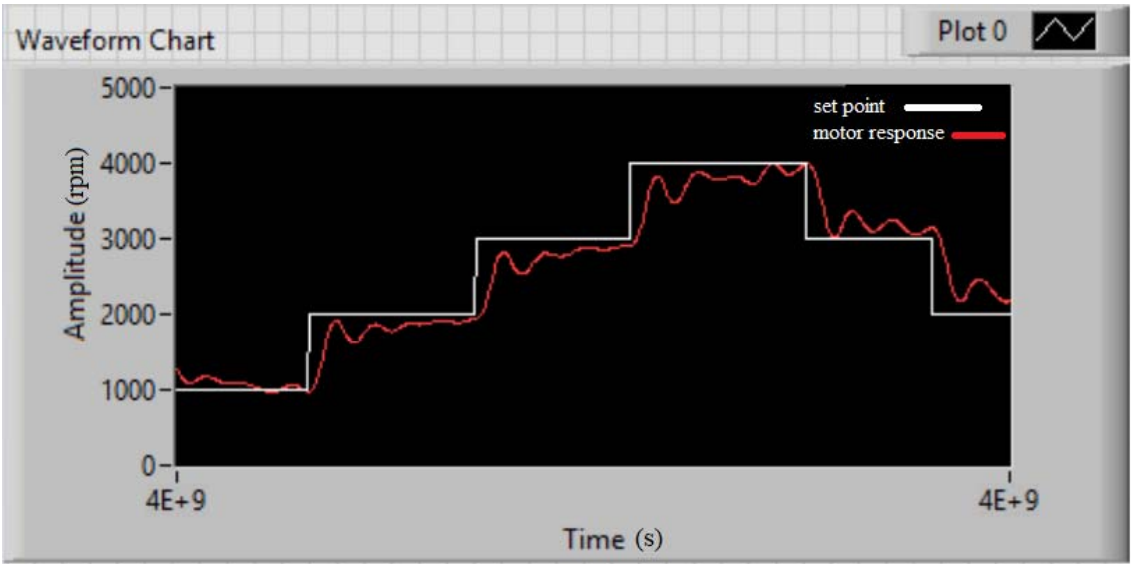


Figure 3.10 Second PI controller result.

The PI controller works well and gives good results in our system, but it takes time to stabilize as we can see in the Figure 3.11.

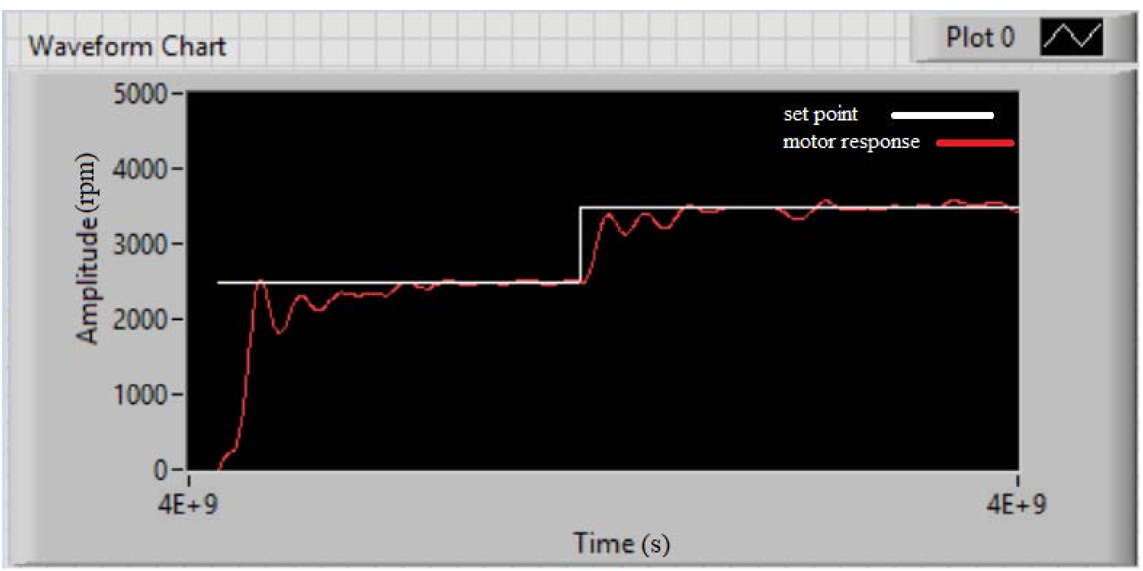


Figure 3.11 Stabilization of the DC motor.

- For the PID controller which has the following parameters Kc= 1.068, Ki= 0.001 and Kd=0.0843., the system is unstable and oscillation occurred. The result is in Figure (3.12):

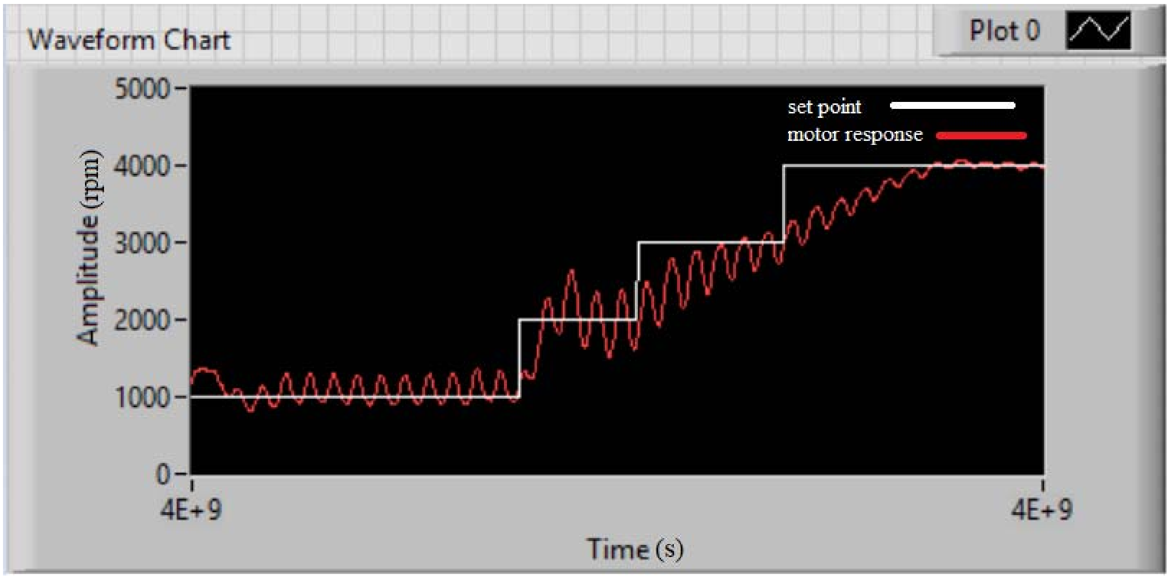


Figure 3.12 PID controller result.

As it is aforementioned this PID controller is unstable for some low speed values. By increasing the speed of the DC motor, we can observe that the system will stabilize at high speed almost at 4000 rpm as we see in the Figure 3.12.

Controller test with load

In order to test the speed controller of the helicopter motors we need to add a load (propellers). as shown in the Figure 3.13.

Figure 3.13 DC motor test with load (propeller).

The result of this test is illustrated bellow in Figure 3.14.

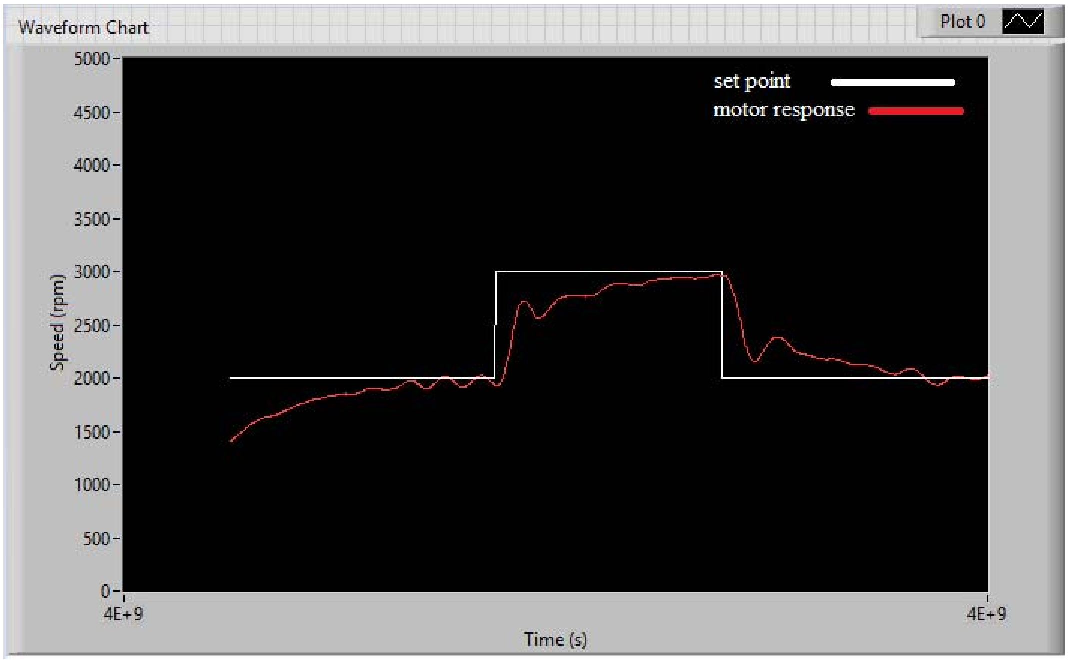


Figure 3.14 load test output response result.

3.1.3 Descussion

For the PI controller the optimal one is the second controller which has the following parameters Kc= 1.068, Ki = 0.0845 because in the first PI there is an overshoot at 1000 rpm desired speed.

The best controller for the speed is the PI controller because it gives acceptable results for both parameters whereas the PID controller causes oscillations and makes the system unstable except for high speeds.We can deduce that the addition of the derivative controller part makes the system noisy.

By applying the load (propeller) to the optimal PI controller. The output respense still tracking the desired speed.

3.2 Position measurement

In this section we deal with the rotary incremental encoder and show its important role in our system, because it gives us the angle by how much does the helicopter rotates in any axis pitch, elevation, or travel. A NI PCI 6221 data acquisition board is used for position or angular measurement.

A LABVIEW program is developed as shown in Figure 3.15 for angular measurement. It uses three signals generated by the rotary encoder, which are the channel A, the 90° phase shift B channel to detect positive or negative angle and the Z channel for each turn or revolution. channel setting, trigger setting and acquire data.

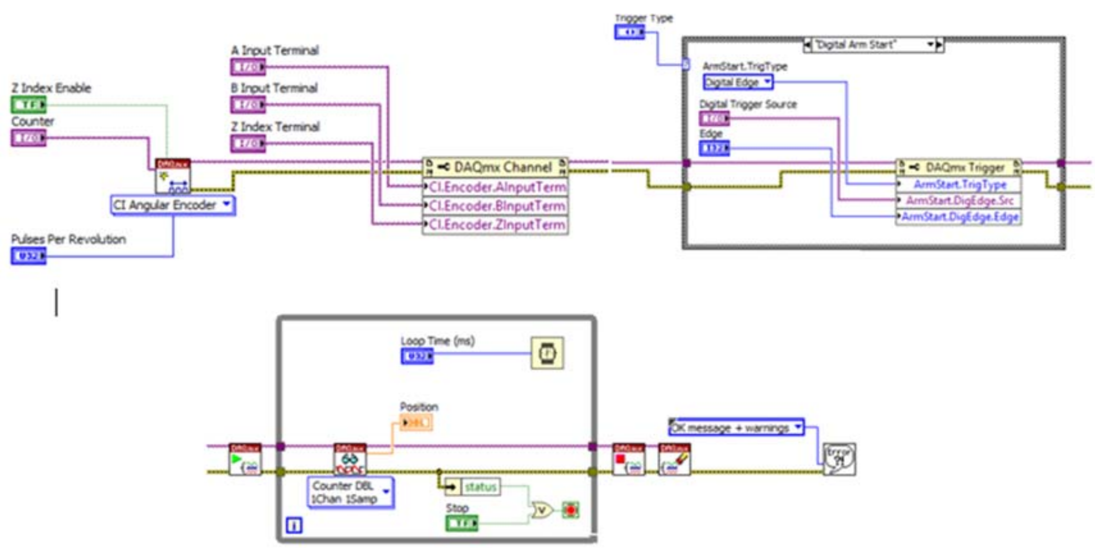


Figure 3.15 Position measurement block diagram.

As explained before that the angular position can be measured by counting the number of pulses where 1000 pulses (resolution of the encoder) refers to 360°.

After connecting the encoder to NI PCI 6221 through SCB 68-A terminal connection board and running the program we can observe the result in the front panel as shown in Figure 3.16.

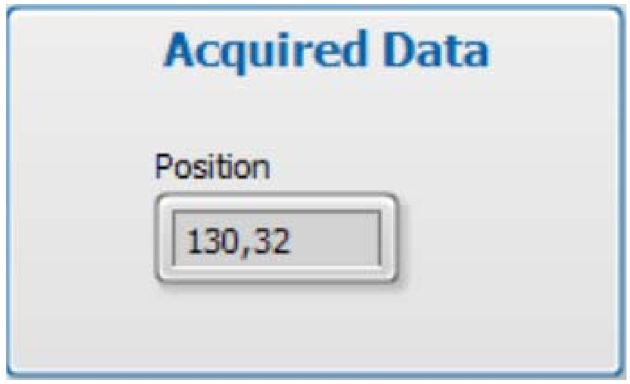


Figure 3.16 Position measurments results.

In the Figure 3.16 the position is in degree. From this result we see that the high resolution of our incremental encoder helps us to have a good evaluation of our position angle which is almost the same angle in real system.

In our system we need three rotary encoders in order to get the exact position for each axis by monitoring the three angles that's why we developed a program that can track more than one angle at the same time we just need to identify new input channels for the other encoders. Figure 3.17 illustrates a connection of two encoders with NI PCI SCB 68-A (see appendix).

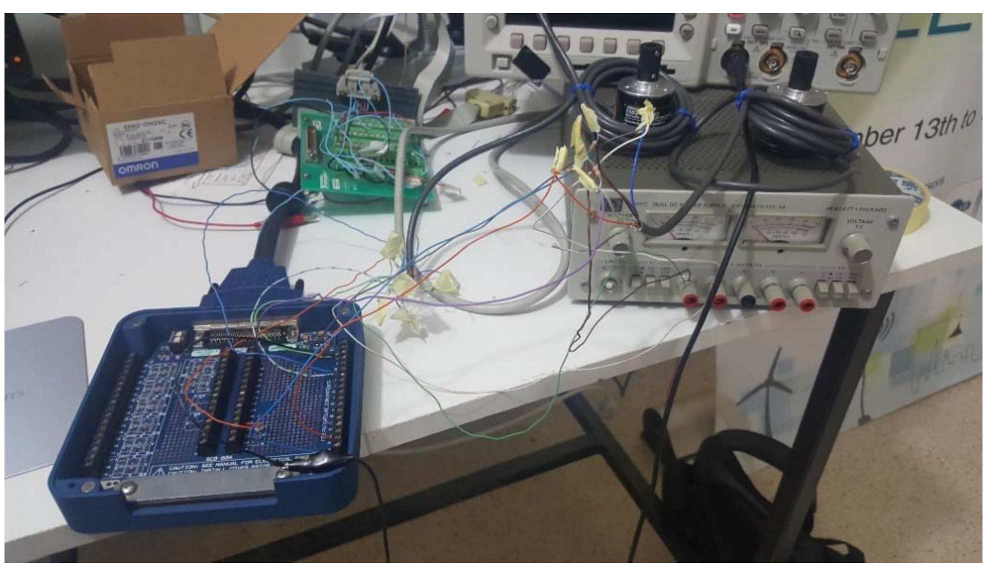


Figure 3.17 Encoders connection to NI PCI SCB 68-A.

The result provided by two rotary encoders working simultaniously is presented in Figure 3.18.

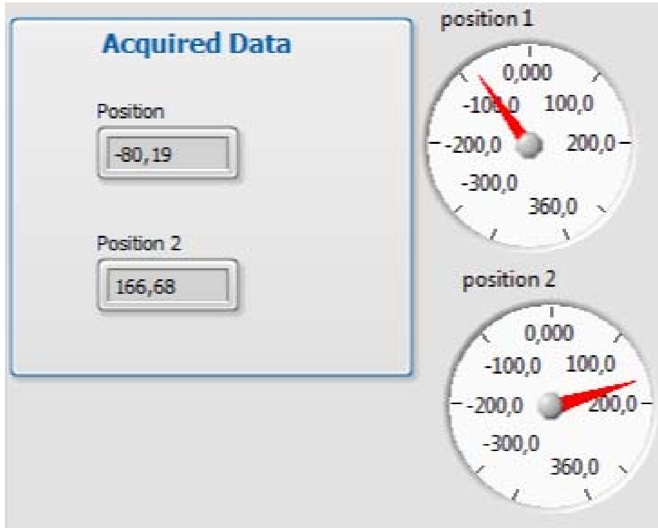


Figure 3.18 Position measurments of two encoders.

This program works successefully and gives accurate results both in positive and negitaive directions. If we want to add another encoder we repeat the same process .

3.2.1 Descussion

In the real time position measurment program, we have used a counters which can count up/down the falling or rising edges as it is specified in the DAQ settings.

In position measurement the incremental encoder works perfectly and gives precise resluts for different angles in both directions .

Resoulution improvement of encoder

When more resolution is needed, it is possible for the counter to count the leading and trailing edges of the quadrature encoder's pulse train from one channel, which doubles (x2) the number of pulses per revolution. Counting both leading and trailing edges of both channels of a quadrature encoder will quadruple (x4) the number of pulses per revolution. As a result, 4,000 pulses per turn can be generated from a 1000 PPR quadrature encoder. Typically, with the encoder, the 4x signal will be accurate to better than ±1 count [15]. (see appendix)

General conclusion

In this project, the DC motors has been driven by a PWM and H-bridge because they cover both of the speed and direction control respectively in order to move the helicopter freely in the three axis.

The H-bridge and PWM was designed in proteus software to be implemented as printed circuit board (PCB) in order to reduce the helicopter weight and avoid the bulky circuits. Experimentally, the designed and printed PWM and H-bridge circuits allow to control the DC motor perfectly.

The system identification of the whole system (combined dc motor, H-bridge and PWM circuits) has been done experimentally by applying a step response. The result was recorded and transfer function was extracted using the first order system identification method, then the PI controller parameters estimation are obtained using SIMULINK.

After accomplishing the DC motor model estimation, the PI controller design is considered to control the speed of the motor. This PI controller was built in LABVIEW, and the data acquisition is performed using a NI-6009 card. The overall system controller has been tested and good results were obtained for the system desired motor speed response. whereas the PID controller causes oscillations and makes the system unstable except for high speeds.

For the position measurment, a rotary encoder connected to an M series NI PCI 6221 SCB 68-A has been used. A LABVIEW program was designed and tested. The results were perfect and accurate.

As perespictive work, the following interelated points can be stated :

- Designing and implementing the mechanical part (3-DOF helicopter).
- Extract the state space model and identify the helicopter parameters
- Design the open loop and closed loop controller of the whole system.
- Controlling the elevation, pitch and travel.

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APPENDIX

Pinout and Signal Descriptions (NI USB-6008/6009)

The following figure shows the pinout of the NI USB-6008/6009. Analog input signal names are listed as single-ended analog input name, AI x, and then differential analog input name, (AI x+/-). Refer to the following table for a detailed description of each signal.

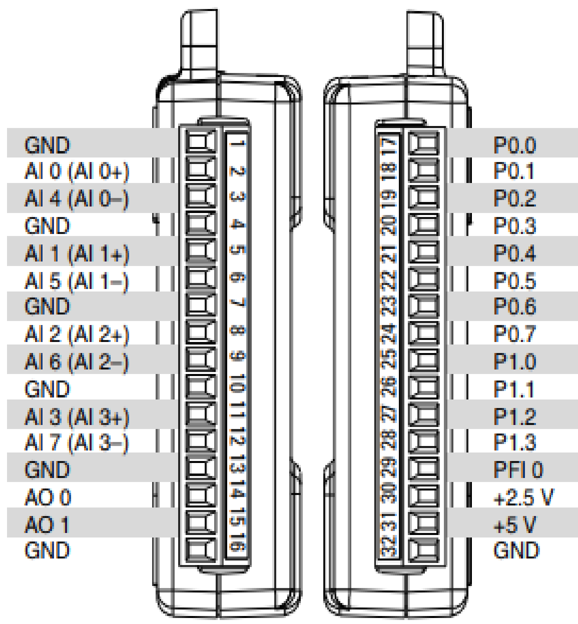

Figure NI USB-6008/6009 Pinout

Table Signal Descriptions (Continued)

Signal Name	Reference	Direction	Description
GND	______	______	Ground—The reference point for the single-ended analog input measurements, analog output voltages, digital signals, +5 VDC supply, and +2.5 VDC at the I/O connector, and the bias current return point for differential mode measurements

AI	Varies	Input	Analog Input Channels 0 to 7—For single-ended measurements, each signal is an analog input voltage channel. For differential measurements, AI 0 and AI 4 are the positive and negative inputs of differential analog input channel 0. The following signal pairs also form differential input channels: AI , AI , and AI .
AO	GND	Output	Analog Output Channels 0 and 1—Supplies the voltage output of AO channel 0 or AO channel 1. Refer to the Analog Output section for more information
P0	GND	Input or Output	Port 0 Digital I/O Channels 0 to 7—You can individually configure each signal as an input or output. Refer to the Digital I/O section for more information
P1	GND	Input or Output	Port 1 Digital I/O Channels 0 to 3—You can individually configure each signal as an input or output. Refer to the Digital I/O section for more information.
PFI 0	GND	Input	PFI 0—This pin is configurable as either a digital trigger or an event counter input. Refer to the PFI 0 section for more information.
+2.5v	GND	Output	+2.5 V External Reference—Provides a reference for wrap-back testing. Refer to the +2.5 V External Reference section for more information
+5 V	GND	Output	+5 V Power Source—Provides +5 V power up to 200 mA. Refer to the +5 V Power Source section for more information.

NI PCI/PXI-6221 Device Pinouts

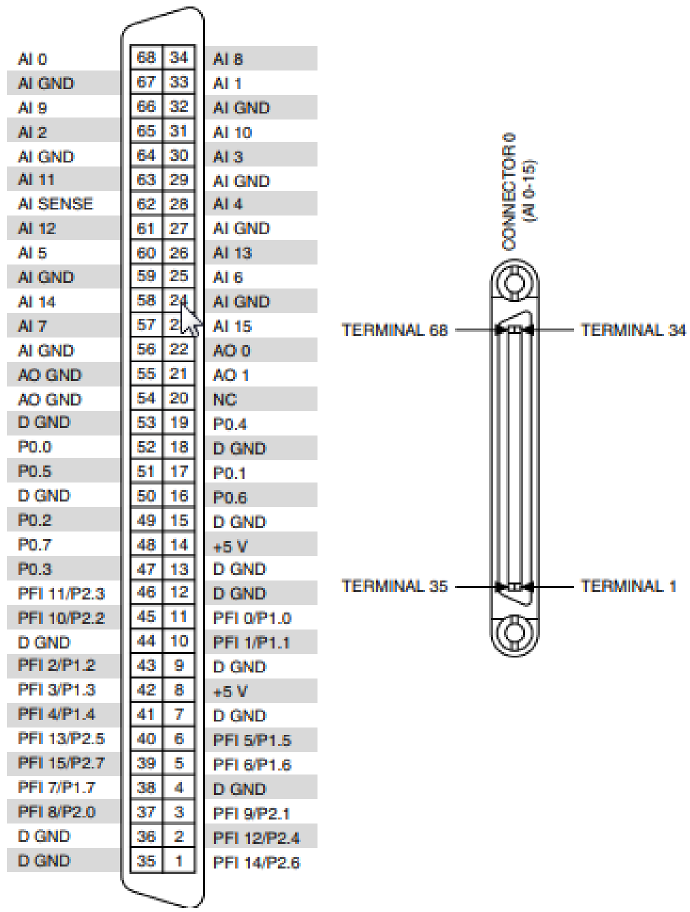

Figure NI PCI/PXI-6221 Pinout

PFI/Port 1/Port 2 Functionality

Functionality	Static digital input, static digital output, timing input, timing output
Timing output	sources Many AI, AO, counter, DI, DO timing signals
Debounce filter settings	Debounce filter settings 125 ns, 6.425 µs, 2.56 ms, disable; high and low transitions; selectable per input

Achieving higher resolution with Quadrature Encoders

To make encoder measurements, you need a basic electronic component called a counter. Based on its several inputs, a basic counter emits a value that represents the number of edges (low to high transitions in the waveform) counted. Most counters have three relevant inputs – gate, source, and up/down. The counter counts the events registered in the source input, and, depending on the state of the up/down line, it either increments the count or decrements it. For example, if the up/down line is "high" the counter increments the count, and if it is "low," the counter decrements the count. Figure 1 shows a simplified version a counter.

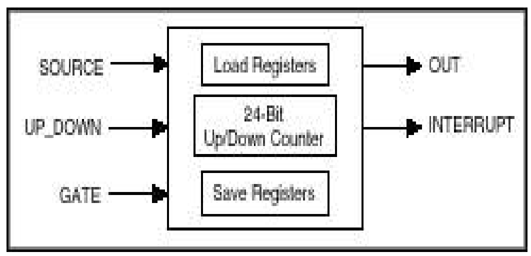

Figure 1 Simplified Model of a Counter

An encoder usually has five wires that you need to connect to the instrument, and, depending on the encoder, these wires vary in color. You can use these wires to provide power to the encoder and to read in the A, B, and Z signals. Figure 2 shows a typical pinout table for an incremental encoder.

Pin	5-pin Single-ended
1	Ground
2	Index
3	A channel
4	+5VDC power
5	B channel

Figure 2 Incremental Encoder Pinout

The next step is determining where you should connect each of these wires. Considering the counter described above, signal A is connected to the source terminal, making this the signal from which the pulses are counted. Signal B is connected to the up/down terminal, and you can connect the +5 VDC and ground signals to any power source – in most cases, a digital line in a data acquisition device card suffices.

Once the edges are counted, the next concept you need to consider is how those values are converted to position. The process by which edge counts are converted to position depends on the type of encoding used. There are three basic types of encoding, X1, X2, and X4.

X1 Encoding

Figure 5 shows a quadrature cycle and the resulting increments and decrements for X1 encoding. When channel A leads channel B, the increment occurs on the rising edge of channel A. When channel B leads channel A, the decrement occurs on the falling edge of channel A.

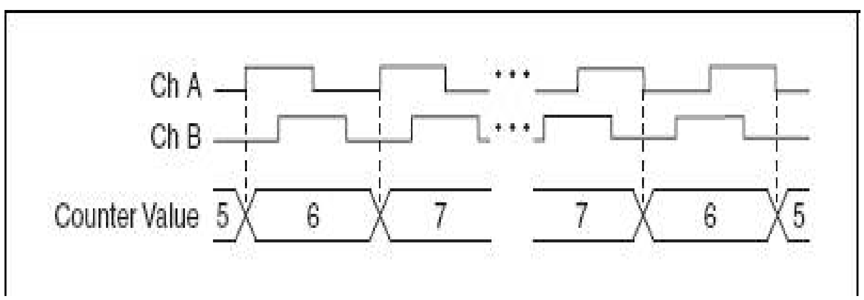

Figure 3 X1 Encoding

X2 Encoding

The same behavior holds for X2 encoding except the counter increments or decrements on each edge of channel A, depending on which channel leads the other. Each cycle results in two increments or decrements, as shown in Figure 6.

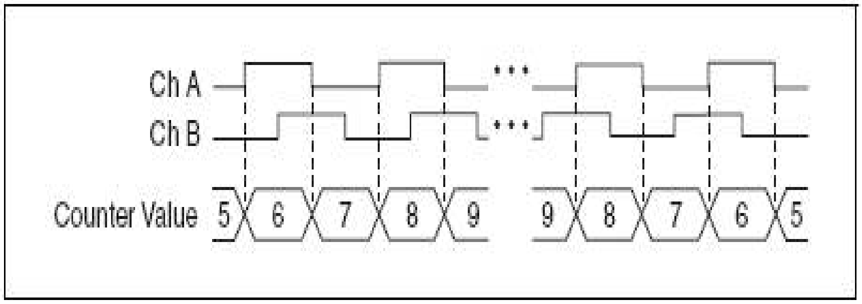

Figure 4 X2 Encoding

X4 Encoding

The counter increments or decrements similarly on each edge of channels A and B for X4 encoding. Whether the counter increments or decrements depends on which channel leads the other. Each cycle results in four increments or decrements, as shown in Figure 5.

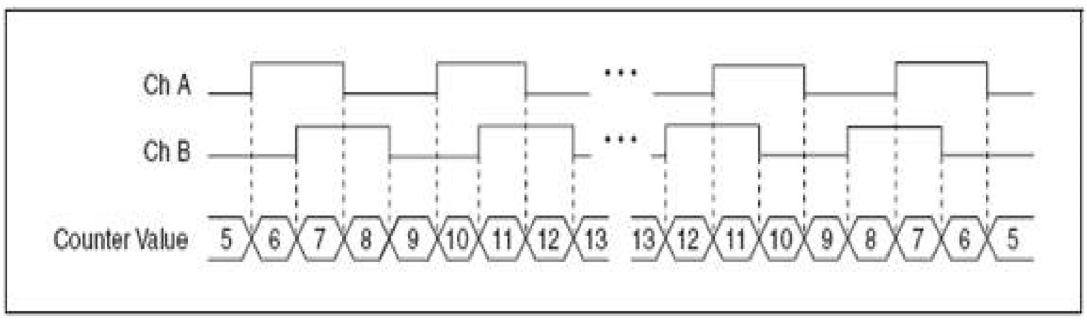

Figure 5 X4 Encoding