Palestine Polytechnic University

College of Engineering & Technology

Mechanical Engineering Department

Project

Modeling and Control of Articulated Hydraulic Manipulator

Project Team

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2010-2011

PROJECT NAME

Modeling and Control of Articulated Hydraulic Manipulator

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According to the directions of the project supervisor and by the agreement of all examination committee members, this project is presented to the department of Mechanical Engineering at College of Engineering and Technology, for partial fulfillment Bachelor of engineering degree requirements.

Supervisor Signature

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Committee Member Signature

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Department Head Signature

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Acknowledgment

We would to acknowledge and extend our heartfelt gratitude to the following persons who have made the completion of this project possible:

To God, who made all things possible

To our advisor, Dr. Yousif Swati, for his vital encouragement and support

To Mr. Majdi Zalloum for the help and inspiration he extended

To Mr. Sadi Hirbawi, for his understanding and assistance

To all mechanical department members and staff

Most especially to our families and friends

Abstract

The articulated hydraulic manipulator is a vertical articulated robot with three revolute joints with gripper attached; the robot has three degree of freedom. Each joint in this robot is driven by hydraulic actuator, this work concerns modeling and control of it, this robot belongs to mechatronics laboratory in Palestine Polytechnic University (PPU), it is a dead robot, and making it alive is the aim of this project.

In order to make this robot alive, many challenging problem will be covered in this project, these problems are kinematics, dynamics, actuation, sensing, motion planning, control, programming, and task planning problems.

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Introduction

1.1 Robotics overview

Robotics is concerned with the study of those machines that can replace human beings in the execution of a task, as regards both physical activity and decision making.

At the present time, the industrial robots have a significant impact on the modern industry, such that the robot can improve the quality of life by freeing workers from dirty, boring, dangerous and heavy labor.

In this text the term robot will mean a computer controlled industrial manipulator. This type of robot is essentially a mechanical arm operating under computer control.

An official definition of such a robot comes from the Robot Institute of America (RIA): A robot is a reprogrammable multifunctional manipulator designed to move material, parts, tools, or specialized devices through variable programmed motions for the performance of a variety of tasks.

1.2 Robot Mechanical Structure

The key feature of robot is its mechanical structure. Robots can be classified as those with a fixed base “Robot manipulators”, and those with a mobile base “mobile robots”, in our case we have a robot with a fixed base.

The mechanical structure of a robot manipulator consist of rigid link connect by joint to form kinematic chain, the joint can be (rotary) revolute or (linear) prismatic. In the case of revolute joint, this joint allows relative rotation between two links, these displacement are called joint angles. While prismatic joint allows a linear relative motion between two links, which called the joint offset.

To construct a manipulator, the first link in a chain is connected base and the last link is connected to the end-effector, this end-effector can be anything from a welding device to a mechanical hand used to manipulate the environment. The kinematic chain of manipulator is characterized by number of degree of freedom (DOF).

1.3 Robotic system

A robot manipulator should be viewed as more than just a series of mechanical linkages. The mechanical arm is just one component in an overall Robotic System, illustrated in Figure (1.1), which consists of the arm, external power source, end-of-arm tooling, external and internal sensors, computer interface, and control computer. Even the programmed software should be considered as an integral part of the overall system, since the manner in which the robot is programmed and controlled can have a major impact on its performance and subsequent range of applications. [1]

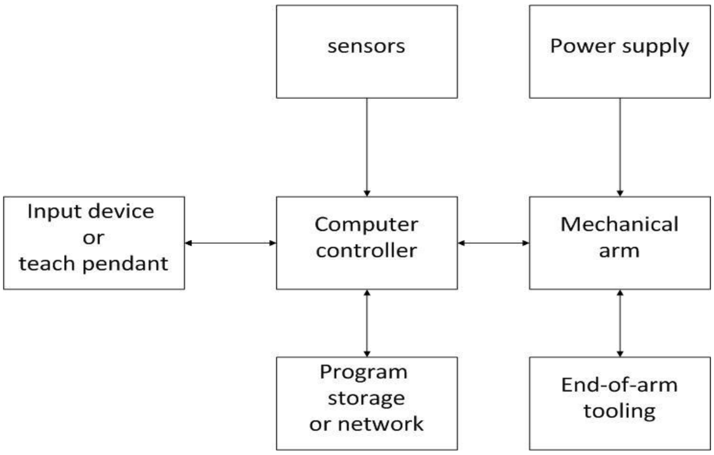

Figure 1.1: Robotic system

1.4 Classification of robots

Robotic manipulators can be classified by several criteria, such as their **power source**, **geometry**, **application area**, or their **method of control**. Such classification is useful primarily in order to determine which robot is right for a given task. For example, a hydraulic robot would not be suitable for food handling or clean room applications. [1]

Power Source: Most robots are electrically, hydraulically, or pneumatically powered. The advantage of use hydraulic power is that the hydraulic actuators are unrivaled in their speed of response and torque producing capability. Therefore hydraulic robots are used primarily for lifting heavy loads.

Application Area: Robots are often classified by application into assembly and non-assembly robots.

Method of Control: Robots are classified by control method into servo and non-servo robots.

Geometry: Robot manipulators are usually classified kinematically on the basis of the first three joints of the arm. The majority of these manipulators fall into one of five geometric types: articulated (RRR), spherical (RRP), SCARA (RRP), cylindrical (RPP), or Cartesian (PPP).

The structure of articulated manipulator is very flexible and has the ability to reach over obstructions. It can generally achieve any position and orientation within the working envelope. As such articulate robots are used for a wide range of applications including paint spraying, arc and spot welding, machine tending, etc. For examples, the articulate robot allows the welding torch to be manipulated in almost the same fashion as a human being would manipulate it. The torch angle and travel angle can be changed to make good quality welds in all positions. Articulated robots also allow the arc to weld in areas that are difficult to reach. In addition, articulate robots are compact and provide the largest work envelope relative to their size. The articulated manipulator is shown in Figure 1.2.

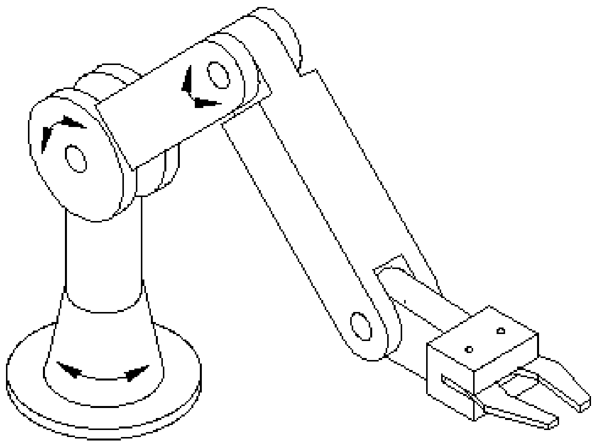

Figure 1.2: Articulated manipulator

1.5 Project Overview

This work concerns modeling and control of an articulated hydraulic manipulator that has three degree of freedom. (Figure 1.3). Each joint in this robot is driven by hydraulic actuator. This robot belongs to mechatronics laboratory in Palestine Polytechnic University (PPU), it is a dead robot, and making it alive is the aim of this project.

In order to make this robot alive, many challenging problem will be covered in this project, these problems are kinematics, dynamics, actuation, sensing, motion planning, control, programming, and task planning problems.

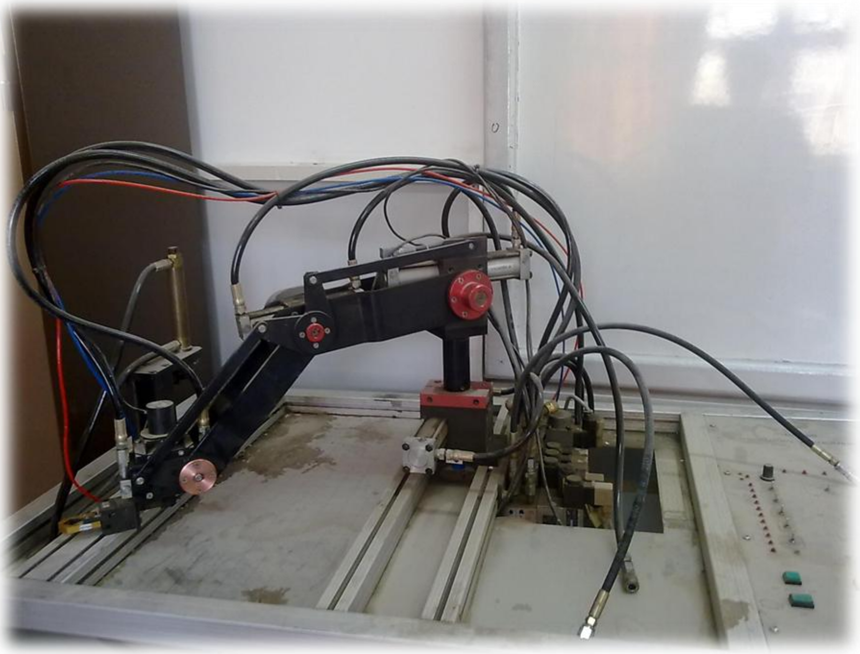

Figure 1.3: Articulated hydraulic manipulator at PPU Lab.

We now provide a brief synopsis of each chapter; Chapter 2 presents solutions to the forward kinematics problem using Denevativ-Haetenberg convention and to the inverse kinematics problem using the geometric approach.

Chapter 3 is concerned with describing motion of the manipulator in terms of trajectories through space.

Chapter 4 presents the dynamic equations of motion which provide the relationships between actuation and contact forces acting on robot mechanisms.

In chapter 5 we study methods of controlling a manipulator (usually with a digital computer) so that it will faithfully track a desired position trajectory through space.

And the remaining chapters concern about experimentation and simulation of the project.

Chapter 2
Kinematics

2.1 Overview

The problem of kinematics is to describe motion without regard to the force which causes it. Within the science of kinematics one studies the position, velocity, acceleration, and all higher order derivatives of the position variables (with respect time or any other variables(s)). Hence, the study of the kinematics of manipulators refers to all the geometrical and time-based properties of the motion. [2]

In this chapter we consider the forward and inverse kinematics for the articulated manipulator, first we consider the forward kinematics problem which is to determine the position and orientation of the end-effector by given the values of joint variables of the robot. Then we solve the inverse kinematics problem which is to determine the values of the joint variables given the end-effector's position and orientation.

To perform the kinematics analysis, we must establish various coordinate frames to represent the positions and orientations of rigid body objects, and with transformations among these coordinate frames.

2.2 Position and Orientation Representation

A rigid body (robot link) is completely described in space by its position and orientation with respect to a reference frame. A coordinate reference frame *i* consists of an origin, denoted *Oi*, and a triad of mutually orthogonal basis vectors, denoted ($\boldsymbol{x}_i$ $\boldsymbol{y}_i$ $\boldsymbol{z}_i$), that are all fixed within a particular body. The pose of a body will always be expressed relative to some other body, so it can be expressed as the pose of one coordinate frame relative to another. Similarly, rigid-body displacements can be expressed as displacements between two coordinate frames, one of which may be referred to as moving, while the other may be referred to as fixed. This indicates that the observer is located in a stationary position within the fixed reference frame, not that there exists any absolutely fixed frame. [3]

2.2.1 Position and displacement

The position of the origin of coordinate frame *i* relative to coordinate frame *j* can be denoted by the 3×1 vector

$$^{j}p_i = \begin{pmatrix} ^{j}p_i^x \\ ^{j}p_i^y \\ ^{j}p_i^z \end{pmatrix} \quad (2.1)$$

The components of this vector are the Cartesian coordinates of O_i in the j frame, which are the projections of the vector $^{j}\boldsymbol{p}_i$ onto the corresponding axes. Figure (2.1)

A translation is a displacement in which no point in the rigid body remains in its initial position and all straight lines in the rigid body remain parallel to their initial orientations. The translation of a body in space can be represented by the combination of its positions prior to and following the translation. Conversely, the position of a body can be represented as a translation that takes the body from a position in which the coordinate frame fixed to the body coincides with the fixed coordinate frame to the current position in which the two fames are not coincident. Thus, any representation of position can be used to create a representation of displacement, and vice versa. [3]

2.2.2 Orientation and Rotation

In order to describe the orientation of a body we will attach a coordinate frame to the body and then give a description of this coordinate system relative to the reference frame. In Figure 2.1 coordinate frame $\{x_i\ y_i\ z_i\}$ has been attached to the body in a known way. A description of frame $\{x_i\ y_i\ z_i\}$ relative to frame $\{x_j\ y_j\ z_j\}$ now suffices to give the orientation of the body. Thus, positions of points are described with vectors and orientations of bodies are described with an attached coordinate frame. One way to describe the body-attached coordinate frame, $\{x_i\ y_i\ z_i\}$, is to write the unit vectors of its three principal axes in terms of the coordinate frame $\{x_j\ y_j\ z_j\}$. [4]

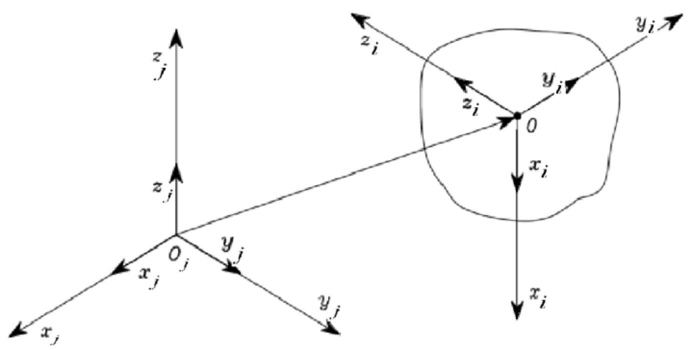

Figure 2.1: Locating an object in position and orientation

Rotation Matrix

The orientation of coordinate frame *i* relative to coordinate frame *j* can be denoted by expressing the basis vectors ($x_i\ y_i\ z_i$) in terms of the basis vectors ($x_j\ y_j\ z_j$). This yields (${}^jx_i\ {}^jy_i\ {}^jz_i$), which when written together as a 3×3 matrix is known as the rotation matrix. The components of ${}^jR_i$ are the dot products of basis vectors of the two coordinate frames.

$$ {}^jR_i = \begin{pmatrix} x_i \cdot x_j & y_i \cdot x_j & z_i \cdot x_j \\ x_i \cdot y_j & y_i \cdot y_j & z_i \cdot y_j \\ x_i \cdot z_j & y_i \cdot z_j & z_i \cdot z_j \end{pmatrix} \qquad (2.2) $$

Because the basis vectors are unit vectors and the dot product of any two unit vectors is the cosine of the angle between them, the components are commonly referred to as direction cosines. Thus, the columns of ${}^j\boldsymbol{R}_i$ specify the direction cosines of the coordinate axis of $(\boldsymbol{x}_i\ \boldsymbol{y}_i\ \boldsymbol{z}_i)$ relative to coordinate axis of ($\boldsymbol{x}_j\ \boldsymbol{y}_j\ \boldsymbol{z}_j$). [3]

The set of $n\times n$ rotation matrices is known as the special orthogonal of order *n,* and is denoted by *SO(n).*for any $R \epsilon SO(3)$ the following properties hold

- $R^T = R^{-1}$
- The columns (and therefore the rows) of *R* are mutually orthogonal
- Each column (and therefore each row) of *R* is a unit vector
- det *R*=1

This explains why rotation matrix ${}^jR_i$ contains nine elements, while only three parameters are required to define the orientation of a body in space.

Rotation matrices are combined through simple matrix multiplication such that the orientation of frame *i* relative to frame *k* can be expressed as

$$ {}^kR_i = {}^kR_j\,{}^jR_i \qquad (2.3) $$

2.2.3 Homogeneous Transformation

Homogeneous transformations combine rotation and translation onto one matrix. A homogeneous transformation has the form

$$ \mathrm{H} = \begin{pmatrix} R & d \\ 0 & 1 \end{pmatrix}, R \epsilon SO(3), d \epsilon R^3 \qquad (2.4) $$

Homogeneous transformation matrices can be used to perform coordinate transformations between frames that differ in orientation and translation. [1]

2.3 Forward Kinematics

Before we begin to solve the forward kinematics problem, the numbers must be assigned to joints and links of robot manipulator. Thus, a robot manipulator with n joint will have *n+1* links, since each joint connects two links. We number the joints from 1 to n, and we number the links from *0 to n*, starting from the base. By this convention, joint *i* connect link *i-1* to link *i*. We will consider the location of joint *i* to be fixed with respect link *i-1*. When joint I is actuated, link i moves. Therefore, in the articulated robot which we study, link 0 (the first link) is fixed, and does not move when the joints are actuated. Joint 1 called waist, joint 2 called shoulder, and joint 3 called elbow as shown in Figure 2.2.

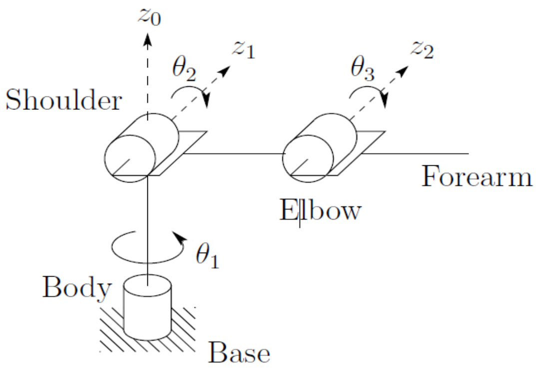

Figure 2.2: The symbolic representation of articulated manipulator

To perform kinematic analysis, we attach a coordinate frame rigidly to each link, we attach $o_i x_i y_i z_i$ to link *i*, this mean that, whatever motion the robot executes, the coordinate of each point on link *i* are constant when expressed in i^{th} coordinate frame. We will assign coordinate frame that satisfy the constraints of Denative-Harternberg convention.

The Denative-Hartenberg Convention

A commonly used convention for selecting frames of reference in robotic is the Denative-Hartenberg Convention. In this convention, each homogeneous transformation A_i is represented as a product of four basic transformations

$$A_i = Rot_{z,\theta i}\ Trans_{z,di}\ Trans_{x,ai}\ Rot_{x,\alpha i}$$

$$A_i = \begin{pmatrix} c_{\theta i} & -s_{\theta i}\, c_{\alpha i} & s_{\theta i}\, s_{\alpha i} & a_i c_{\theta i} \\ s_{\theta i} & c_{\theta i}\, c_{\alpha i} & -c_{\theta i}\, s_{\alpha i} & a_i s_{\theta i} \\ 0 & s_{\alpha i} & c_{\alpha i} & d_i \\ 0 & 0 & 0 & 1 \end{pmatrix} \quad (2.5)$$ *

Where the four quantities θ_i, a_i, d_i, α_i *are* parameters associated with link *i* and joint *i*. This shown in Figure 2.3. [1]

The attach frames according to Denative-Hartenberg Convention having the following feature.

(DH1) The axis x_i is perpendicular to the axis z_{i-1}.
(DH2) The axis x_i intersects the axis z_{i-1}.

These two properties are illustrated in Figure 2.3

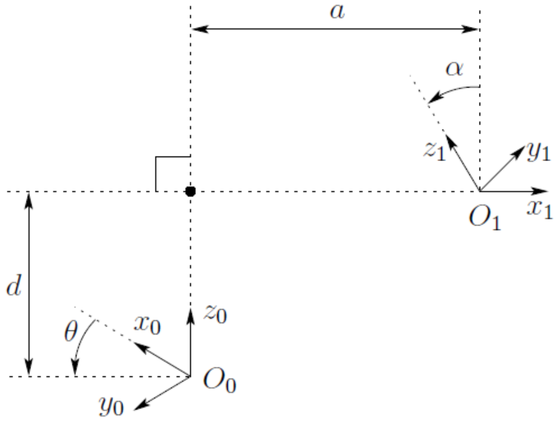

Figure 2.3: Coordinate frames satisfying assumptions DH1 and DH2

The transformation is then described by the following four parameters known as DH Parameters:

a - is the distance between the axes z_i *and* z_{i+1}, *and* its measured along the axis x_{i+1}.
α - is the angel between the axes z_i *and* z_{i+1}, measured in a plane normal to x_{i+1}.
d - is the distance from the origin o_i to the intersection of the x_{i+1} axis with z_i measured along the z_i axis.
θ - is the angel from x_i *to* x_{i+1} measured in a plane normal to z_i.

We use the shorthand notation $s_{\theta i} = sin\theta_i$, $c_{\theta i} = cos\theta_i$, $s_{\alpha i} = sin\alpha_i$, $s_{\alpha i} = sin\alpha_i$ *where i=1,2,3,..*

The articulated manipulator is represented symbolically with attached frames by Figure 2.4. We choose the coordinate frames that satisfy DH convention.

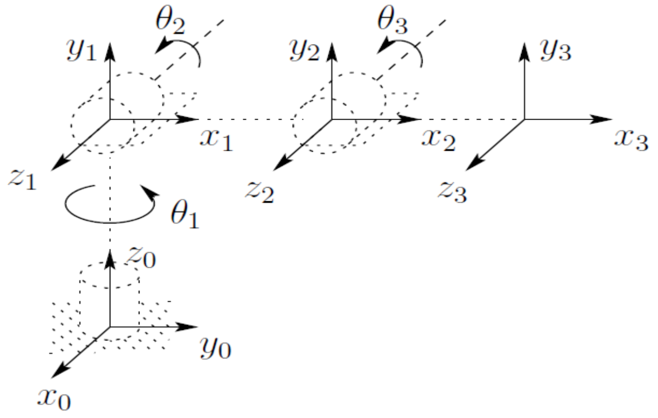

Figure 2.4 Coordinate frames attached to articulated manipulator

The DH parameters for the articulated manipulator are shown in Table2.1.

Link	a_i	α_i	α_i	θ_i
1	*0*	$\pi/2$	α_1	θ_1
2	a_2	*0*	*0*	θ_2
3	a_3	*0*	*0*	θ_3

Table 2.1: DH parameter of the articulated manipulator

The A-matrices are determined from Equation (2.5) as

$$A_1=\begin{pmatrix} c_1 & 0 & s_1 & 0 \\ s_1 & 0 & -c_1 & 0 \\ 0 & 1 & 0 & d_1 \\ 0 & 0 & 0 & 1 \end{pmatrix} \qquad A_2=\begin{pmatrix} c_2 & -s_2 & 0 & a_2\,c_2 \\ s_2 & c_2 & 0 & a_2\,s_2 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} \qquad (2.6)$$

$$A_3=\begin{pmatrix} c_3 & -s_3 & 0 & a_3\,c_3 \\ S_3 & c_3 & 0 & a_3\,s_3 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

The homogeneous transformation "T-matrices" are thus given by

$$T_1^o = A_1$$

$$T_2^o = A_1 A_2 = \begin{pmatrix} c_1c_2 & -c_1s_2 & s_1 & a_2c_1c_2 \\ s_1c_2 & s_1s_2 & -c_1 & a_2s_1c_2 \\ s_2 & c_1 & 0 & a_2s_2+d_1 \\ 0 & 0 & 0 & 1 \end{pmatrix} \qquad (2.7)^*$$

$$T_3^o = A_1 A_2 A_3 = \begin{pmatrix} c_1c_{23} & -c_1s_{23} & s_1 & a_3c_1c_{23}+a_2c_1c_2 \\ s_1c_{23} & s_1s_{23} & -c_1 & a_3s_1c_{23}+a_2s_1c_2 \\ s_{12} & c_{23} & 0 & a_3s_{23}+a_2s_2+d_1 \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

Notice that the first two entries of the last column of T_3^o are the *x, y, and z* components of the origin O_3 in the base frame; that is,

$$x = a_3c_1c_{23}+a_2c_1c_2$$

$$y = a_3s_1c_{23}+a_2s_1c_2 \qquad (2.8)$$

$$z = a_3s_{23}+a_2s_2+d_1$$

are the coordinate of the end effector in the base frame. The rotational part of T_3^o gives the orientation of the frame O_3 relative to the base frame.

2.4 Inverse Kinematics

The problem of inverse kinematics is to determine the end effector's position and orientation in terms of joint variables. We used a geometric approach to find θ_1, θ_2, θ_3 corresponding to given position of the end effector "which represent by point O_c". The components of O_c denoted by x_c, y_c, z_c, as shown in Figure 2.5.

We use the shorthand notation $s_k = \sin\theta_k$, $c_k = \cos\theta_k$, $s_{ij} = \sin(\theta_i+\theta_j)$, $c_{ij} = \cos(\theta_i+\theta_j)$ where: k,i,j =1,2,3 for trigonometric function.

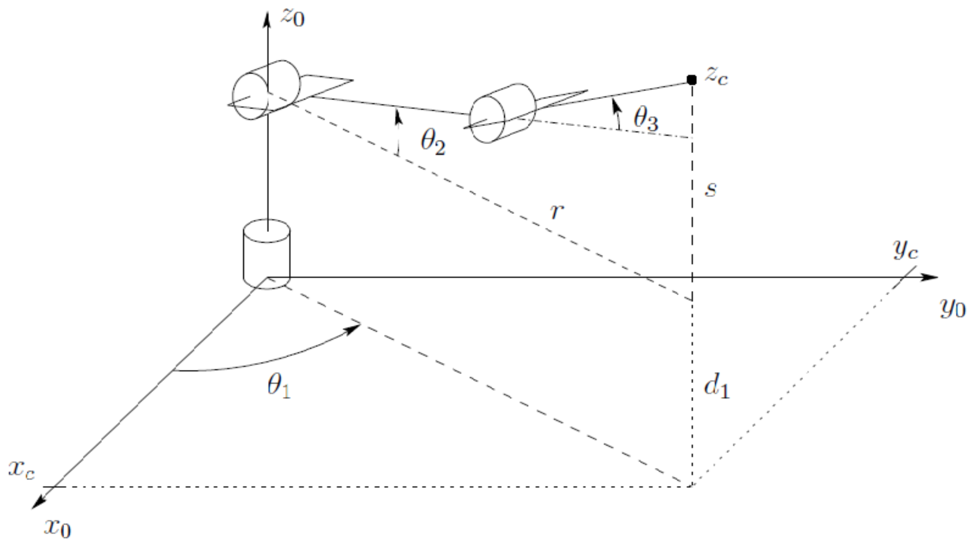

Figure 2.5: Represent point O_c in the base frame

To find θ_1, we project O_c in the $x_0 - y_0$ plane as shown in Figure2.6. We see from this projection that

$$\theta_1 = \text{Atan2}\,(x_c, y_c)\ * \qquad (2.9)$$

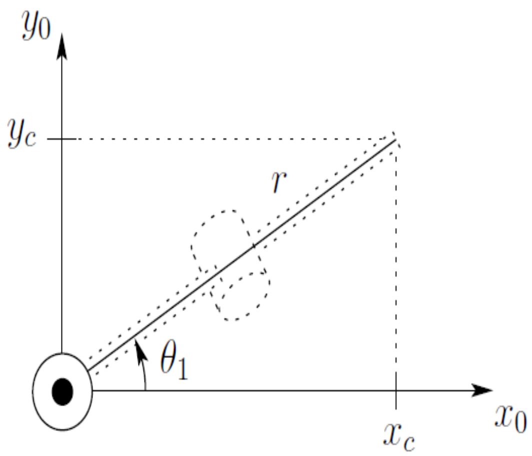

Figure 2.6: Projection of O_c onto $x_0 - y_0$ plane

Atan2 (x, y) denotes the two argument arctangent function

To find the angels θ_2, θ_3 for the articulated manipulator given θ_1, we consider the plane formed by second and third links as shown in Figure2.7. Since the motion of second and third link is planer.

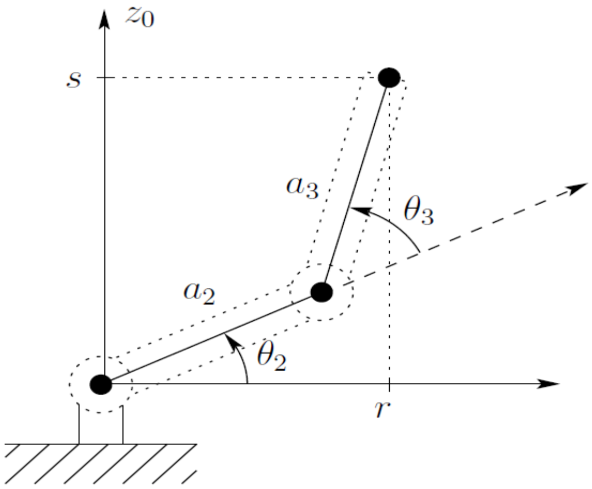

Figure 2.7: Projection of O_c onto the plane formed by links 2 and 3

θ_2 is given as

θ_2 = Atan2 (γ, s) – Atan2 ($a_2+a_3c_3$, $a3s3$) *(2.10)*

=Atan2 ($\sqrt{x_c^2 + y_c^2 - d^2}$, ($z_c$- d_1)) - Atan2 ($a_2+a_3c_3$, $a3s3$)

Using the law of cosines we see that the angle θ_3 is given by

$$\text{Cos } \theta_3 = \frac{\gamma^2 + s^2 - a_2^2 - a_3^2}{2a_2a_3}$$

$$= \frac{x_c^2 + y_c^2 - d^2 + (z_c - d_1) - a_2^2 - a_3^2}{2a_2a_3} = D \quad (2.11)$$

Since $\gamma^2 = x_c^2 + y_c^2 - d^2$ *and* $s = (z_c - d_1)$. *Hence,* θ_3 is given by

$$\theta_3 = \text{Atan2 } (D, \pm\sqrt{1 - D^2})$$

The two solutions for θ_3 correspond to the elbow-down position and elbow-up position, respectively, as shown in Figure 2.8.

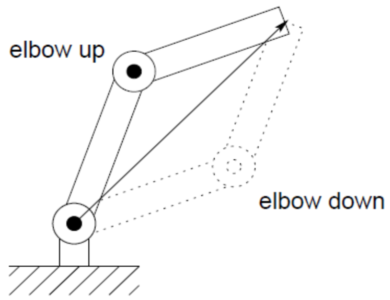

Figure 2.8: Elbow-down and elbow-up position

2.5 The Workspace

The workspace of manipulator is the total volume swept out by the end effector as the manipulator executes all possible motions. The workspace is constrained by the geometry of the manipulator as well as mechanical constrains on the joints.[1] The mechanical limits in the articulated robot limit the motion of revolute joint to the value that appears in Table2.2. These values are measured experimentally.

Axis Movement	Axis Range
Axis1: Base rotation	$-67<\theta_1<113$
Axis2: Shoulder rotation	$-45<\theta_2<45$
Axis: Elbow rotation	$-135<\theta_3<-45$

Table 2.2: The axis range for each joint

The workspace of articulated manipulator is shown in Figure 2.9.

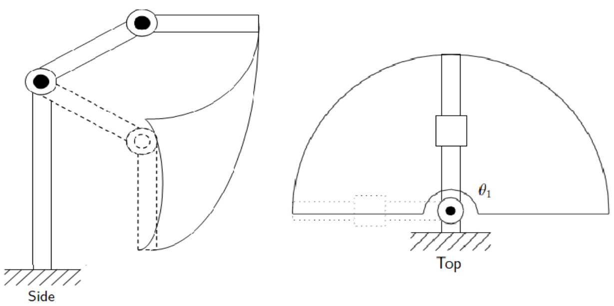

Figure 2.9: workspace of articulated manipulator

Chapter 3
Trajectory generation

3.1 Introduction

The basic problem of this chapter is to move the manipulator arm from an initial position to some desired final position with respect to reference frame. So what we want to plan in this chapter is the trajectory; the trajectory refers to a time history of position, velocity and acceleration for each of the DOF; Planning each of the DOF independently and then assume that the motion is realizable as hole.

This problem includes the human interface problem of how we wish to specify a trajectory or path through space. Thus the user should not write down complicated functions of space and time to specify the task. Rather, we must allow the capability of specifying trajectories with simple descriptions of the desired motion. [2]

When we dealing with trajectory there are many constrains we expect to see in solving this problem, these constrains could be:

1. Spatial constrains, if we have an obstacle in the environment that we don’t want to collide with. We will neglected this constrain in our project and assume that there is no obstacle in the workspace of the robot arm.
2. Time constrain, if the motion has to be done in particular time.
3. Smoothness, we want the manipulator to have a smooth motion because that uses less energy and easy to control.

The solution of trajectory problem can be considered in two main spaces, joint space and Cartesian space. In joint space schemes it’s easy to go through point, there is no problem with singularity, and need less calculation. In other hand, the actual end-effector path in this approach can’t be predicted, and can’t follow straight line.

The trajectory planning in Cartesian space may involve problems difficult to solve. However, Cartesian schemes are more computationally expensive to execute since at run time, inverse kinematics must be solved at the path update rate. Other major problem that we may face in Cartesian space scheme is singularity; if there are some points on the path that the manipulator should follow are in singular configuration. But in this scheme we can specify the shape of the path between path points.

In our approach we will use joint space schemes to solve the trajectory planning problem of articulated manipulator; we will do that to avoid dealing with the complexity of Cartesian space schemes, because we just want to move the end-effector from initial position to final position in smooth way without regard to the path that going on.

3.2 Joint Space Trajectories

The joint space scheme is a method of path generation in which the path shapes (in space and in time) are describe in terms of function of joint angles.

Each path joint is usually specified in terms of a desired position and orientation of the tool frame, relative to the base frame, each of these points is converted into a set of desired joint angles by application of the inverse kinematics. Then a smooth function is found for each of the *n* joints to describe the motion between the initial and final point.

Through the remaining of this chapter we interest in establishing formulas for the angles for each DOF as a function of time in the case that the initial and final points on the path and traveling time are specified (point-to-point).

3.3 Point-to-point motion

In point-to-point motion, the manipulator has to move from an initial to final configuration in a given time t_f. In this case, the actual end-effector path is of no concern. In some cases, there may be constrains on the trajectory. Nevertheless, it is easy to realize that there are infinitely many trajectories that will satisfy a finite number of constrains on the end points. It is common practice therefore to choose trajectories from a finitely parameterizable family, for example, polynomials of degree n, where n depends on the number of constrains to be satisfied. [1] This is the approach that we will take in this project.

In our approach we consider two functions to create a trajectory for point-to-point motion, Cubic Polynomial and Linear Segment with Parabolic Blend, these smooth functions then substitute onto the dynamics equation of the robot to see which the function produces less torque and thus less power consumption.

3.3.1 Cubic Polynomials

Consider the problem of moving the end-effector from its initial position to final position in a particular time. The set of goal joint angles can be calculated using the inverse kinematics. The initial position of the manipulator is also known in the form of a set of joint angles. To make a smooth motion between the initial and final position of manipulator, we wish first to generate a polynomial joint trajectory between two configurations, and we wish specify the start and end velocities for the trajectory. This gives four constrains that the trajectory must satisfy. Two constrains on the function's value come from the selection of initial and final values:

$$\theta(0) = \theta_0 \qquad (3.1)$$

$$\theta(t_f) = \theta_f$$

The other constrains come from the velocity. If we need the function to be continuous in velocity, the initial and final velocity must be zero:

$$\dot{\theta}(0) = 0 \qquad (3.2)$$

$$\dot{\theta}(t_f) = 0$$

These four constrains can be satisfied by a polynomial of at least third degree. Since a cubic polynomial has four independent coefficients, it can be made to satisfy these constrains. A cubic has the form

$$\theta(t)=a_0+a_1t+a_2t^2+a_3t^3 \qquad (3.3)$$

and so the joint velocity and acceleration is given as

$$\dot{\theta}(t) =a_1+2a_2t+3a_3t^2 \qquad (3.4)$$

$$\ddot{\theta}(t) = 2a_2+6a_3t$$

Combine the equation (3.3) and (3.4) with the four constraints yields four equation in four unknowns:

$$\theta_0 =a_0$$

$$\theta_f =a_0+a_1t_f+a_2t_f^2+a_3t_f^3 \qquad (3.5)$$

$$0 = a_0$$

$$0 = a_1 + 2a_2 t_f + 3a_3 t_f^2$$

Solving these equations for the a_i we obtain

$$a_0 = \theta_0$$

$$a_1 = 0$$

$$a_2 = \frac{3}{t_f^2}(\theta_f - \theta_0) \qquad (3.6)$$

$$a_3 = -\frac{2}{t_f^3}(\theta_f - \theta_0)$$

Using (3.6) we can calculate the cubic polynomial that connects any initial joint angle position with any desired final position. This solution is for the case when the joint starts and finishes at zero velocity. Figures 3.1 Show cubic polynomial trajectory.

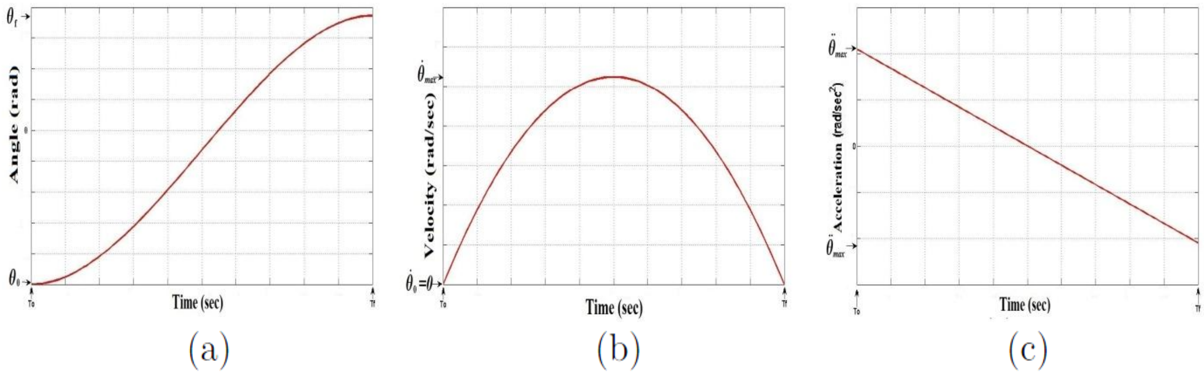

Figure 3.1: (a) Cubic polynomial trajectory. (b) Velocity profile for cubic polynomial trajectory. (c) Acceleration profile for cubic polynomial trajectory.

When we apply this method to the articulated manipulator; the end-effector is moving in a smooth path as shown in Figure 3.2. This is a special case when we move the end-effector from point (0,0,0) to point (20,15,20) in 5 sec, this shape will be appeared when we moving the manipulator in various points in space. The corresponding trajectory for each joint is shown in Figure 3.3. While Figure 3.4 and

Figure 3.5 show the velocity profile and acceleration profile for cubic polynomial trajectory for each joint. Figure 3.6 shows the corresponding torque for each joint.*

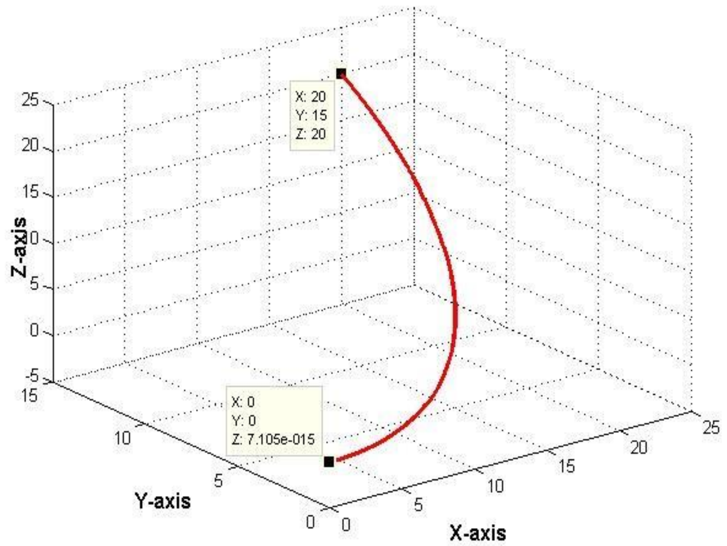

Figure 3.2: End-effector path for cubic polynomial trajectory for articulated manipulator

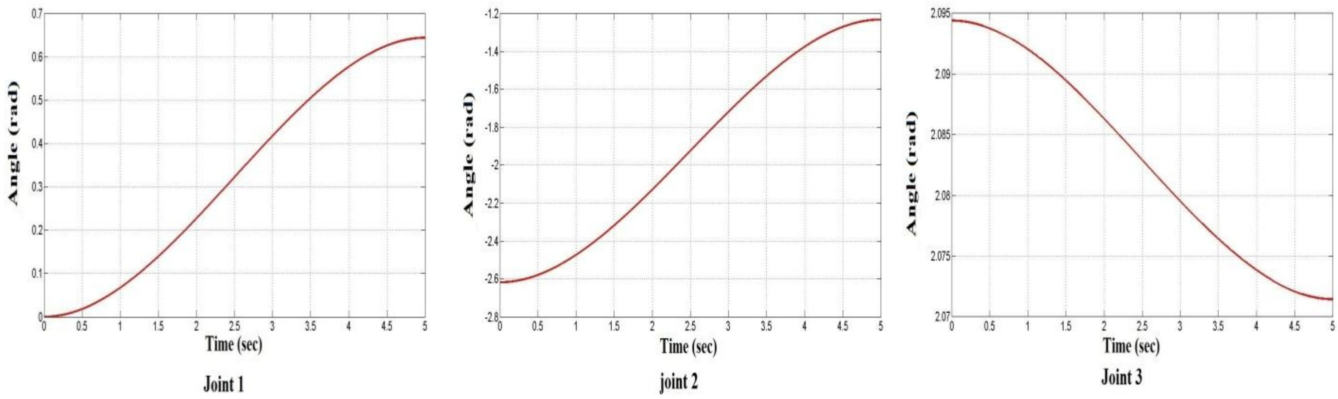

Figure 3.3: Cubic polynomial trajectory for articulated manipulator

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These Figures come from the execution of Matlab script for LSPB trajectory and Dynamics for LSPB for articulated manipulator in Appendix A

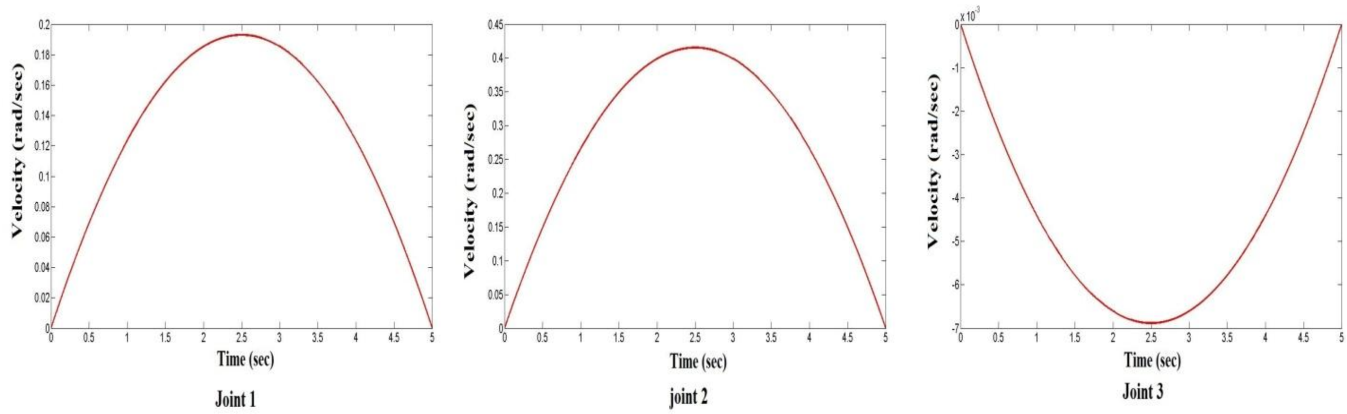


Figure 3.4: Velocity profile for cubic polynomial trajectory for articulated manipulator

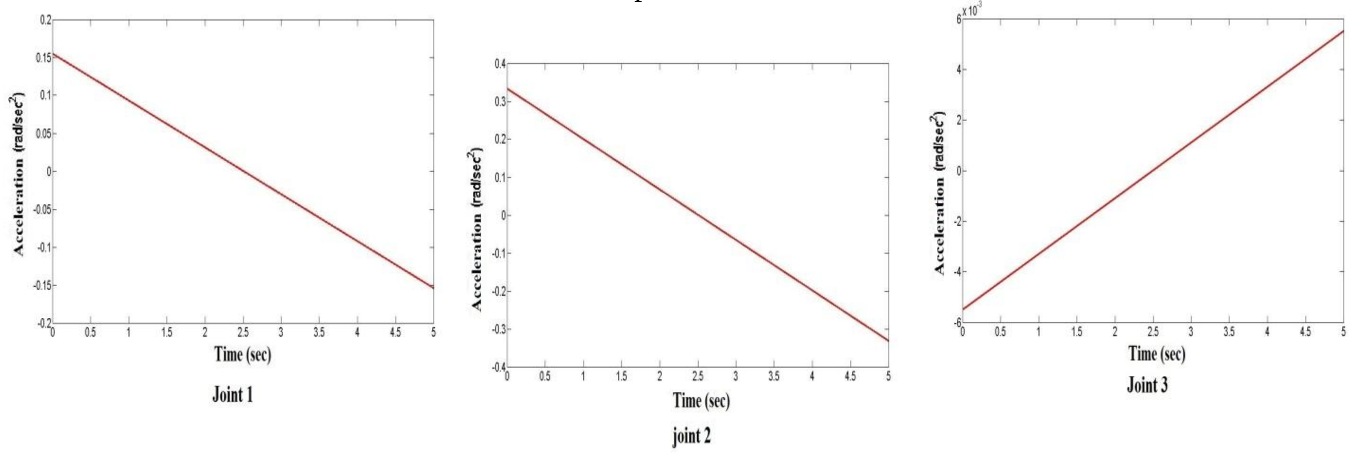


Figure 3.5: Acceleration profile for cubic polynomial trajectory for articulated manipulator

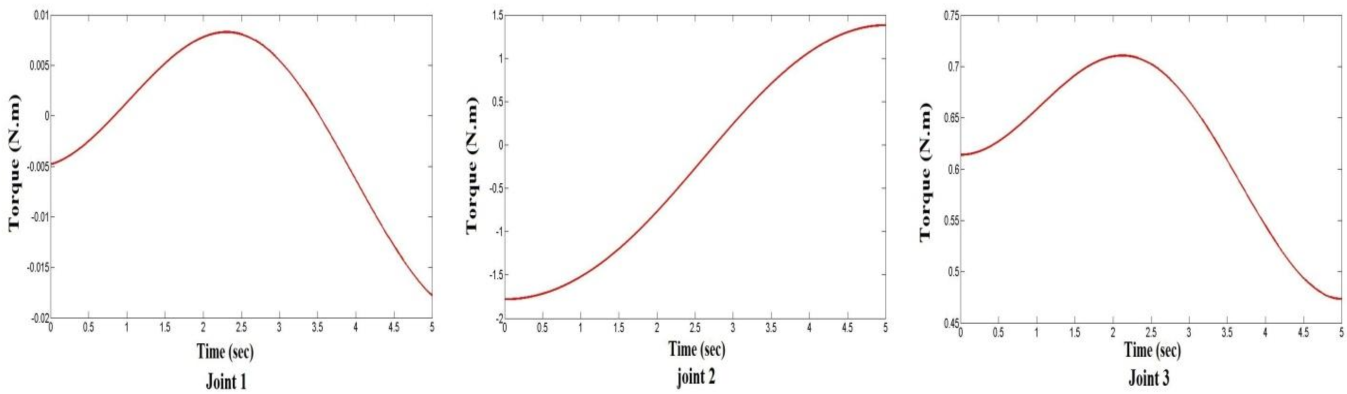


Figure 3.6: Torque curves for each joint for cubic polynomial trajectory

3.3.2 Linear Segment with Parabolic Blends (LSPB)

Another way to generate suitable joint space trajectories is by using so called Linear Segment with Parabolic Blends (LSPB). This type of trajectory has a Trapezoidal Velocity Profile.

This is a linear function but we add a parabolic blend region at the beginning and end of the path. These blend regions create a smooth path with continuous position and velocity. Thus, during the blend portion of the trajectory, constant acceleration is used to change velocity smoothly. Figure 3.3 shows a simple path constructed in this way.

In order to construct this single segment we will assume that the parabolic blends both have the same duration, and therefore the same constant acceleration is used during both blends.

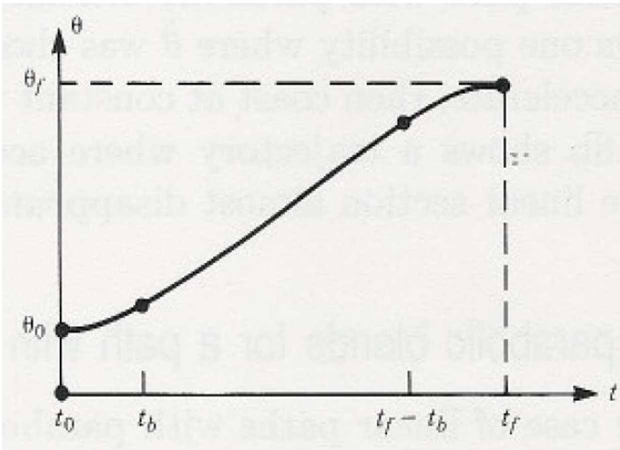


Figure 3.7: Linear segment with parabolic blends

In order to construct this single segment we will assume that the parabolic blends have the same duration, and therefore the same constant acceleration is used during both blends. As indicated in Figure 3.7, there are many solutions to the problem, but note that the answer is always symmetric about the halfway point in time, t_h, and about the halfway point in position, θ_h. The velocity at the end of the blend region must equal the velocity of the linear section, and so we have

$$\ddot{\theta} = \frac{\theta_h - \theta_b}{t_h - t_b} \quad (3.7)$$

Where θ_b is the value of θ at the end of the blend region, and $\ddot{\theta}$ is the acceleration acting during the blend region. The value of θ_b is given by

$$\theta_b = \theta_0 + \frac{1}{2}\ddot{\theta}t_b^2 \tag{3.8}$$

Combining (3.7) and (3.8) and $t = 2t_h$, we get

$$\ddot{\theta}t_b^2 - \ddot{\theta}tt_b + (\theta_f - \theta_0) = 0 \tag{3.9}$$

where t is the desired duration of the motion. Given any θ_f,θ_0, and t. Usually, (3.9) solved for the corresponding t_b, and the acceleration $\ddot{\theta}$ is chosen. The choice of acceleration must be sufficiently high, or a solution will not exist. Solving (3.9) for t_b, we obtain

$$t_b = \frac{t}{2} - \frac{\sqrt{\ddot{\theta}^2 t^2 - 4\ddot{\theta}(\theta_f - \theta_0)}}{2\ddot{\theta}} \tag{3.10}$$

The constraint on the acceleration used in the blend is

$$\ddot{\theta} \geq \frac{4\,(\theta_f - \theta_0)}{t^2} \tag{3.11}$$

The complete LSPB trajectory is given by

$$\theta(t) = \begin{cases} \theta_0 + \frac{1}{2}\ddot{\theta}t^2, & 0 \leq t \leq t_b \\ \theta_0 + \ddot{\theta}t_b(t - \frac{t_b}{2}), & t_b < t \leq t_f - t_b \\ \theta_f - \frac{1}{2}\ddot{\theta}(t_f - t)^2, & t_f - t_b < t \leq t_f \end{cases} \tag{3.12}$$

and so the joint velocity and acceleration is given as

$$\dot{\theta}(t) = \begin{cases} \ddot{\theta}t, & 0 \leq t \leq t_b \\ \ddot{\theta}t_b t, & t_b < t \leq t_f - t_b \\ \ddot{\theta}(t_f - t), & t_f - t_b < t \leq t_f \end{cases} \tag{3.13}$$

$$\ddot{\theta}(t) = \begin{cases} \ddot{\theta}, & 0 \le t \le t_b \\ \ddot{\theta} t_b, & t_b < t \le t_f - t_b \\ \ddot{\theta}, & t_f - t_b < t \le t_f \end{cases} \tag{3.14}$$

Using (3.12) we can calculate the LSPB trajectory that connects any initial joint angle position with any desired final position. Figure 3.8 shows a LSPB trajectory and the velocity and acceleration curves.

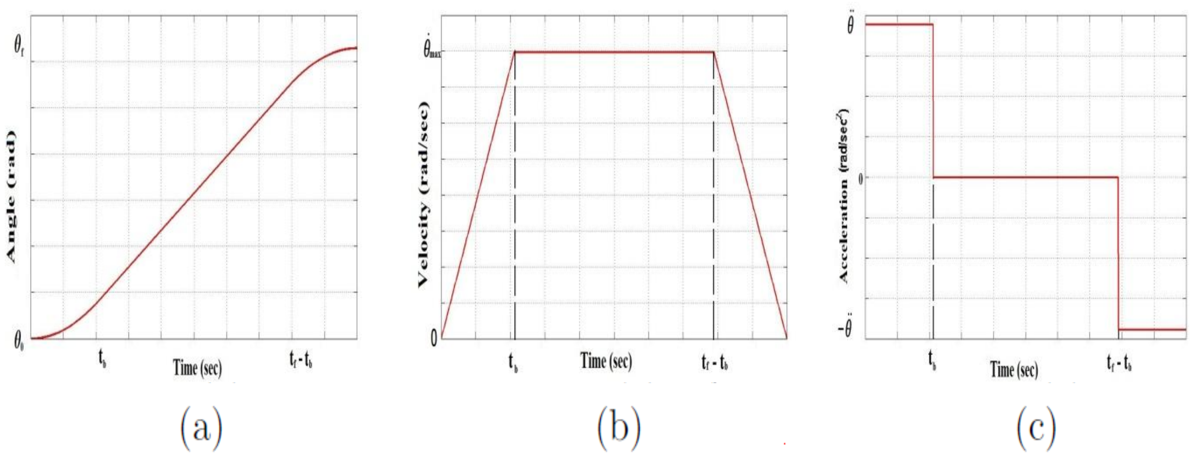


Figure 3.8: (a) LSPB trajectory (b) Velocity profile for LSPB trajectory (c) Acceleration profile for LSPB trajectory

When we apply LSPB method to the articulated manipulator; the end-effector is moving in a smooth path as shown in Figure 3.8. We choose the acceleration $\ddot{\theta}$ = 0.7 (rad/sec^2) to move the end-effector from point (0,0,0) to point (20,15,20) in 5 second. The corresponding trajectories for each joint are shown in Figure 3.9. While Figure 3.10 and Figure 3.11 show the velocity profile and acceleration profile for LSPB trajectory for each joint. Figure 3.13 shows the corresponding torque for each joint.*

These Figures come from the execution of Matlab script for LSPB trajectory and Dynamics for LSPB for articulated manipulator in Appendix A

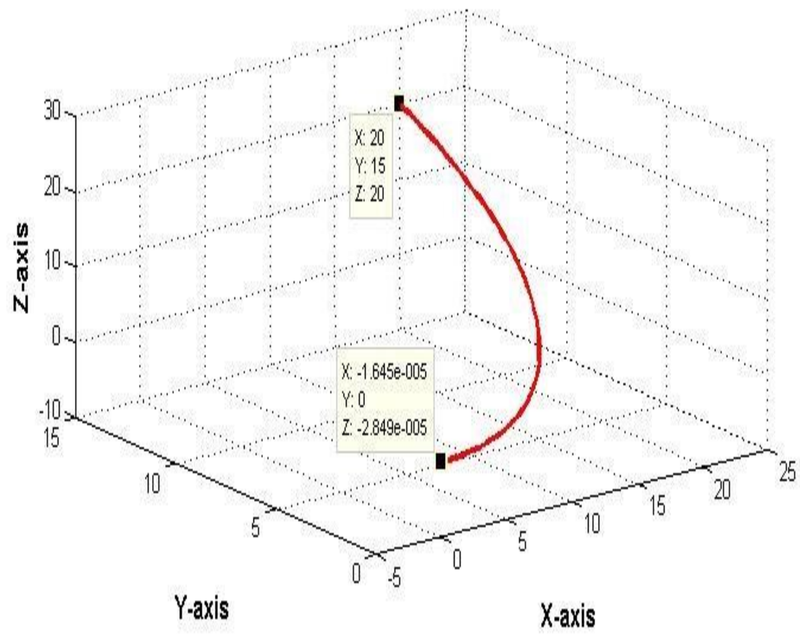


Figure 3.9: End-effector path of LSPB trajectory for articulated manipulator

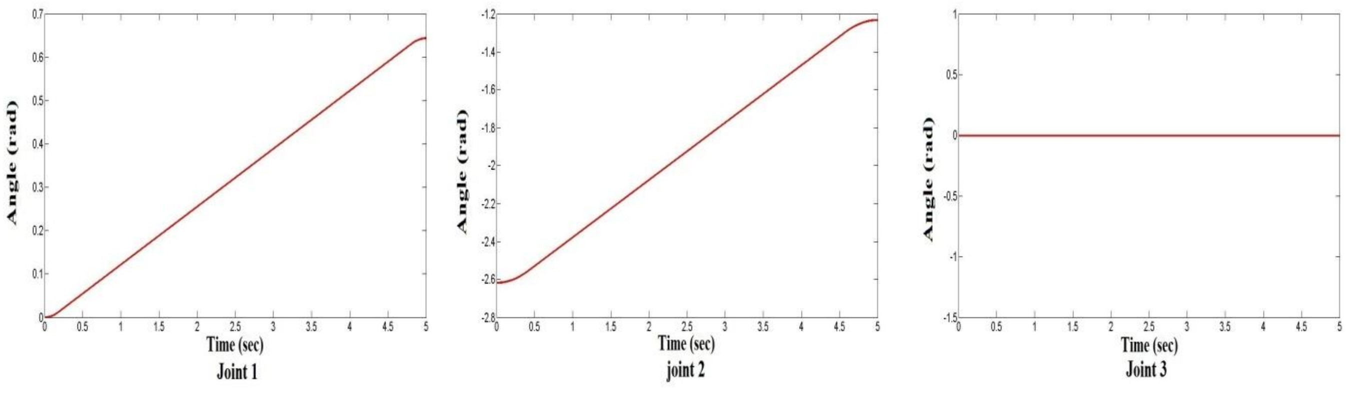


Figure 3.10: LSPB for articulated manipulator

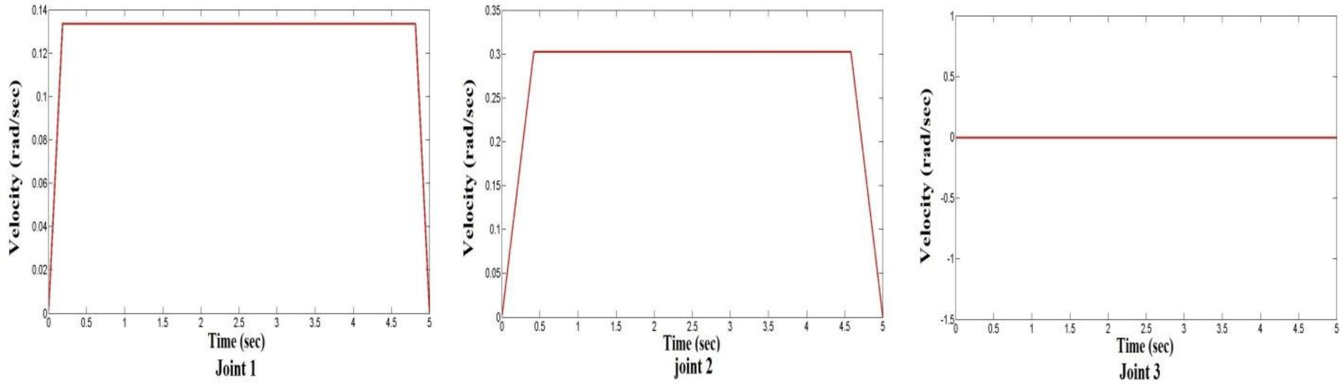


Figure 3.11: Velocity profile for LSPB trajectory for articulated manipulator

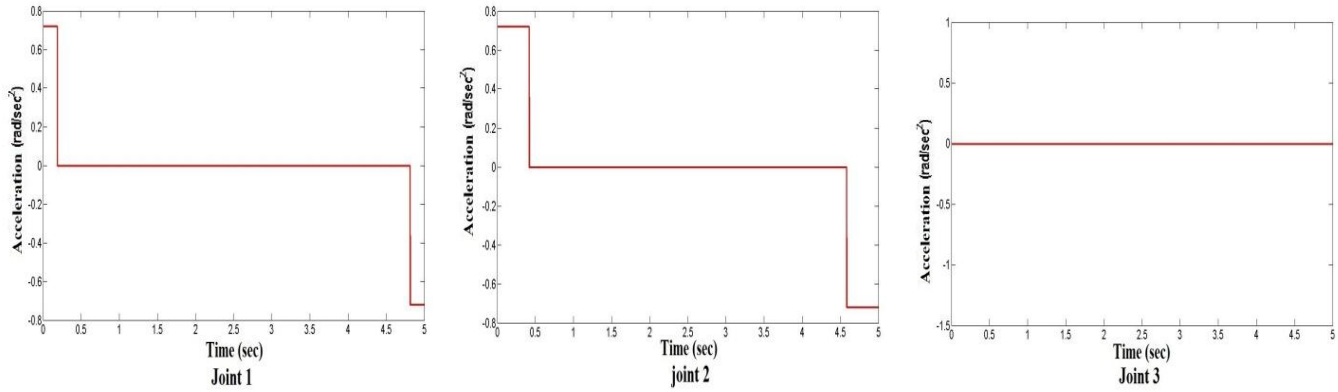


Figure 3.12: Acceleration profile for LSBP trajectory for articulated manipulator

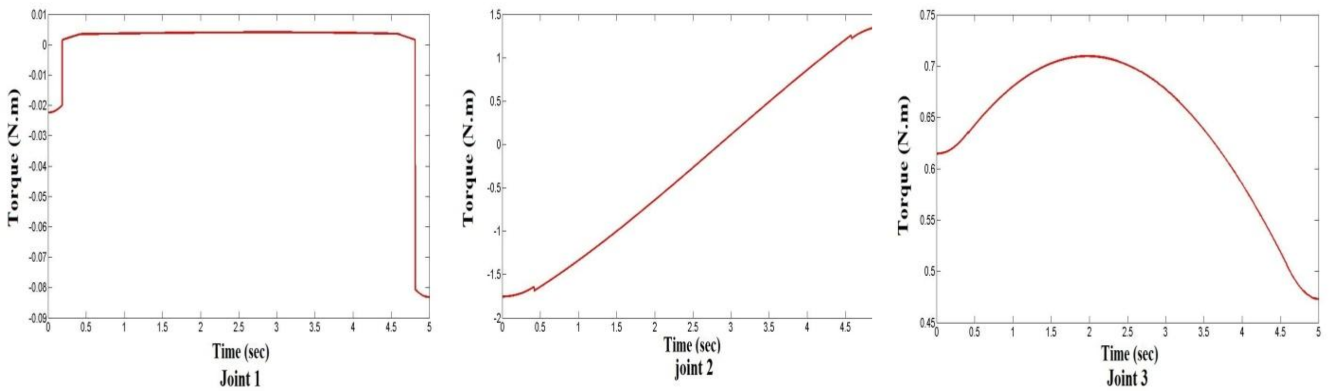


Figure 3.13: Torque curves for each joint for LSPB trajectory

We see from the torque curve for cubic polynomial and LSPB trajectories that the maximum torque produced by these methods approximately equal. Which means approximately same power consumption, so, our choice between these methods according to power consumption will not be the best choice. Thus, we will choose the cubic polynomial method since it easier to program and need less user specification than LSPB method.

Chapter 4
Dynamic modeling

4.1 Introduction

In this chapter we will construct the dynamic modeling of the articulated manipulator. Whereas the kinematic equation derive in previous chapters describe the motion without regard of the forces and torque producing the motion, the dynamic equations describe the relationship between force and motion. The equations of motion play an important rule for simulation of motion, analysis, and design of control algorithms.

In order to construct the dynamic modeling and find the equations of motion of articulated robot we will use the Euler-Lagrange equations.

4.2 Equation of motion

In this section we apply the Euler-Lagrange equations to the articulated manipulator and derive the corresponding equations of motion. We can write Euler-Lagrange equations as

$$D(\theta)\,\ddot{\theta} + c(\theta,\dot{\theta})\dot{\theta} + g(\theta) = \tau \qquad (4.1)$$

Where $D(\theta)$ is the inertia matrix, and its symmetric and positive definite for any manipulator.

$$D(\theta) = [\textstyle\sum_{i=1}^{n}\{m_i J_{vi}(\theta)^T J_{vi}(\theta) + j_{wi}(\theta)^T R_i(\theta) I_i R_i(\theta)^T J_{wi}(\theta)\}] \qquad (4.2)$$

Where $J_{vi}(\theta)$ is the Jacobian of linear velocity, $J_{wi}(\theta)$ is the Jacobian of angular velocity, R_i is the rotation matrix, and I_i is the inertia tensor.

The $(k,j)^{th}$ element of the matrix $C(\dot{\theta},\theta)$ is defined as

$$c_{kj} = \sum_{i=1}^{n} c_{ijk}\ (\theta)\dot{\theta}_i$$

$$= \sum_{i=1}^{n}\left\{\frac{\partial d_{kj}}{\partial \theta_i} + \frac{\partial d_{ki}}{\partial \theta_j} - \frac{\partial d_{ij}}{\partial \theta_k}\right\}\dot{\theta}_i \qquad (4.3)$$

And the gravity vector $g(\theta)$ is given by

$$g(\theta) = \{\theta_1(\theta), \dots\dots, \theta_n(\theta)\}^T \quad (4.4)$$

To apply the Euler-Lagrange equation on our robot, let us fix notation as follow. For $i=1,2,3$, θ_i denotes the joint angle which also serves as a generalized coordinate; m_i denotes the mass of link *i; d_1,a_1*, and a_2 denotes the length of links *1,2 and 3* respectively *;* l_{ci} denotes the distance from the previous joint to the center of mass of link *i*; and I_i denotes the moment of inertia of link *i* about the z-axis, passing through the center of mass of link *i.* (See Figure 4.1)

We will use the Denavit-Hartenberg joint variables as generalized coordinates, which allow us to make effective use of the Jacobian expressions in computing inertia matrix.

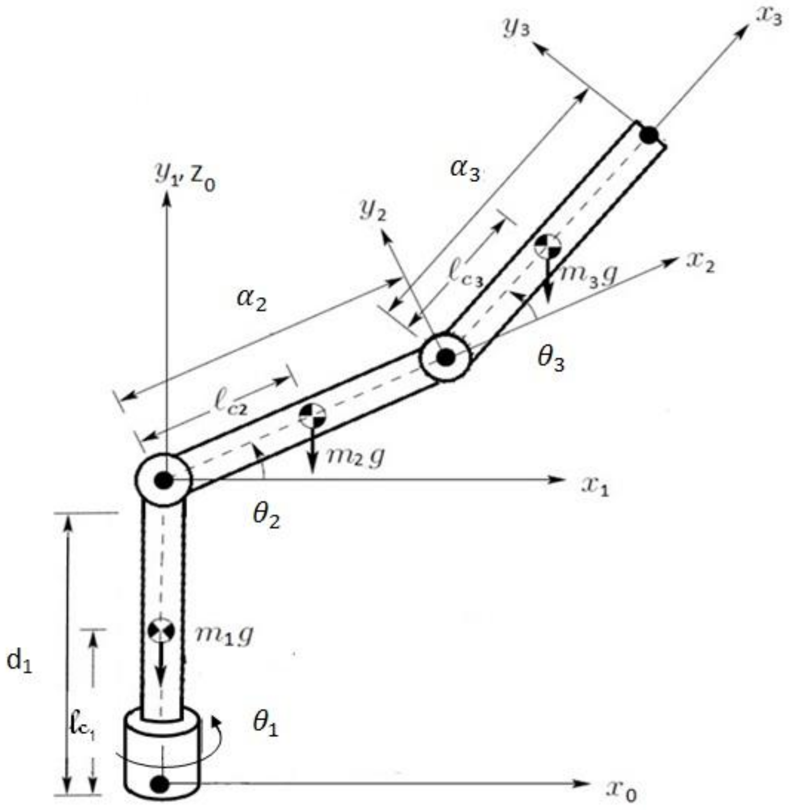


Figure 4.1: 3DOF Articulated Manipulator

The Jacobian of linear velocity for *i* links are

$$J_{vc1} = [z_0 x(o_{c1} - o_0) \quad 0 \quad 0] \tag{4.5}$$

$$J_{vc2} = [z_0 x(o_{c2} - o_0) \quad z_1 x(o_{c2} - o_1) \; 0]$$

$$J_{vc2} = [z_0 x(o_{c3} - o_0) \quad z_1 x(o_{c3} - o_1) \; z_2 x(o_{c3} - o_2)]$$

The Jacobian of angular velocity for *i* links are

$$J_{w1} = [z_0 \quad 0 \quad 0] \tag{4.6}$$

$$J_{w2} = [z_0 \quad z_1 \quad 0]$$

$$J_{w3} = [z_0 \quad z_1 \quad z_2]$$

The origin of the DH frames are given by

$$o_0 = \begin{bmatrix} 0 \\ 0 \\ 0 \end{bmatrix} \qquad o_1 = \begin{bmatrix} 0 \\ 0 \\ d_1 \end{bmatrix} \qquad o_2 = \begin{bmatrix} a_2 \cos\theta_1 \cos\theta_2 \\ a_2 \sin\theta_1 \cos\theta_2 \\ a_2 \sin\theta_2 + d_1 \end{bmatrix} \tag{4.7}$$

And the origins at the center of mass for each link are given by

$$o_{c1} = \begin{bmatrix} 0 \\ 0 \\ l_{c1} \end{bmatrix} \qquad o_{c2} = \begin{bmatrix} l_{c2} \cos\theta_1 \cos\theta_2 \\ l_{c2} \sin\theta_1 \cos\theta_2 \\ l_{c2} \sin\theta_2 + d_1 \end{bmatrix} \tag{4.8}$$

$$o_{c3} = \begin{bmatrix} l_{c3} \cos\theta_1 \cos(\theta_2 + \theta_3) + a_2 \cos\theta_1 \cos\theta_2 \\ l_{c3} \sin\theta_1 \, cos(\theta_2 + \theta_3) + a_2 \sin\theta_1 \, cos\,\theta_2 \\ l_{c3} \sin(\theta_2 + \theta_3) + a_2 \sin\theta_2 + d_1 \end{bmatrix}$$

And the axis of rotation z_{i-1} given by

$$z_0 = \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix} \qquad z_1 = \begin{bmatrix} \sin\theta_1 \\ -\cos\theta_1 \\ 0 \end{bmatrix} \qquad z_2 = \begin{bmatrix} \sin\theta_1 \\ -\cos\theta_1 \\ 0 \end{bmatrix} \tag{4.9}$$

Performing the required calculations then yields

$$J_{vc1} = [0]$$

$$J_{vc2} = \begin{bmatrix} -l_{c2} \cos\theta_2 \sin\theta_1 & -l_{c2} \cos\theta_1 \sin\theta_2 & 0 \\ l_{c2} \, cos\,\theta_1 \cos\theta_2 & -l_{c2} \sin\theta_1 \, sin\,\theta_2 & 0 \\ 0 & l_{c2} \cos\theta_2 & 0 \end{bmatrix} \tag{4.10}$$

$$J_{vc3} = \begin{bmatrix} -l_{c3}\sin\theta_1\cos(\theta_2+\theta_3) - a_2\sin\theta_1\cos\theta_2 & -l_{c3}\cos\theta_1\sin(\theta_2+\theta_3) - a_2\cos\theta_1\sin\theta_2 & -l_{c3}\cos\theta_1\sin(\theta_2+\theta_3) \\ l_{c3}\cos\theta_1\, cos(\theta_2+\theta_3) + a_2\, cos\,\theta_1\, cos\,\theta_2 & -l_{c3}\, sin\,\theta_1\, sin(\theta_2+\theta_3) - a_2\, sin\,\theta_1\, sin\,\theta_2 & -l_{c3}\sin\theta_1\, sin(\theta_2+\theta_3) \\ 0 & a_2\cos\theta_2 + l_{c3}\cos(\theta_2+\theta_3) & l_{c3}\cos(\theta_2+\theta_3) \end{bmatrix}$$

$$J_{w1}=\begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 1 & 0 & 0 \end{bmatrix}$$

$$J_{w2}=\begin{bmatrix} 0 & \sin\theta_1 & 0 \\ 0 & -\cos\theta_1 & 0 \\ 1 & 0 & 0 \end{bmatrix} \qquad (4.11)$$

$$J_{w3}=\begin{bmatrix} 0 & \sin\theta_1 & sin\,\theta_1 \\ 0 & -\cos\theta_1 & -cos\,\theta_1 \\ 1 & 0 & 0 \end{bmatrix}$$

By substitute in Equation (4.2) this yield

$$D(\theta) = \begin{bmatrix} d_{11} & d_{12} & d_{13} \\ d_{21} & d_{23} & d_{23} \\ d_{31} & d_{32} & d_{33} \end{bmatrix} \qquad (4.12)$$

Where

$$d_{11} = I_{yy1} + I_{zz2} + I_{zz3} + m_3(l_{c3}\, cos(\theta_2+\theta_3) + a_2\, cos\,\theta_2) + l_{c2}^2 m_2 \cos^2\theta_2$$

$$d_{12} = d_{21} = 0 \qquad ; d_{13} = d_{31} = 0$$

$$\begin{aligned} d_{22} = m_2 l_{c2}^2 &+ I_{yy2} cos^2(\theta_1-\theta_2) + I_{yy3} cos^2(\theta_1-\theta_3) + I_{yy2} sin^2(\theta_1-\theta_2) \\ &+ I_{yy3} sin^2(\theta_1-\theta_3) \\ &+ m_3[a_2^2 + l_{c3}^2 + 2a_2 l_{c3}(\sin(\theta_2+\theta_3)\sin\theta_2 + \cos(\theta_2+\theta_3)\cos\theta_2)] \end{aligned}$$

$$d_{23} = d_{32} = I_{yy3} cos^2(\theta_1-\theta_3) + I_{xx3} sin^2(\theta_1-\theta_3) + m_3(l_{c3}^2 + a_2 l_{c3}\cos\theta_3)$$

$$d_{33} = m_3 l_{c3}^2 + I_{yy3} cos^2(\theta_1-\theta_3) + I_{xx3} sin^2(\theta_1-\theta_2)$$

Now, we can compute the Christoffel symbols using Equation (4.3). This gives

$$c_{111} = 0$$

$$c_{121} = c_{211} = \frac{1}{2}\frac{\partial d_{11}}{\partial \Theta_2} = \frac{1}{2}(-m_3 l_{c3} \sin(\Theta_2 + \Theta_3) - m_3 a_2 \sin\Theta_2 - 2m_2 l_{c2}^2 \cos\Theta_2 \sin\Theta_2)$$

$$c_{131} = c_{311} = \frac{1}{2}\frac{\partial d_{11}}{\partial \Theta_3} = -\frac{1}{2}\, m_3 l_{c3} \sin(\Theta_2 + \Theta_3)$$

$$c_{221} = -\frac{1}{2}\frac{\partial d_{22}}{\partial \Theta_1} = (I_{yy2} - I_{xx2}) \sin(\Theta_1 - \Theta_2)\cos(\Theta_1 - \Theta_2) + (I_{yy3} - I_{xx2}) \sin(\Theta_1 - \Theta 3)\cos(\Theta 1 - \Theta 3)$$

$$c_{231} = c_{321} = -\frac{1}{2}\frac{\partial d_{23}}{\partial \Theta_1} = (I_{yy3} - I_{xx3})\ \sin(\Theta_1 - \Theta_3)\cos(\Theta_1 - \Theta_3)$$

$$c_{331} = -\frac{1}{2}\frac{\partial d_{33}}{\partial \Theta_1} = (I_{yy3} - I_{xx3}) \sin(\Theta_1 - \Theta_3)\cos(\Theta_1 - \Theta_3)$$

$$c_{112} = -\frac{1}{2}\frac{\partial d_{11}}{\partial \Theta_2} = \frac{1}{2}(m_3 l_{c3} \sin(\Theta_2 + \Theta_3) + m_3 a_2 \sin\Theta_2 + 2m_2 l_{c2}^2 \cos\Theta_2 \sin\Theta_2)$$

$$c_{122} = c_{212} = \frac{1}{2}\frac{\partial d_{22}}{\partial \Theta_1} = (I_{xx2} - I_{yy2}) \sin(\Theta_1 - \Theta_2)\cos(\Theta_1 - \Theta_2) + (I_{xx2} - I_{yy3}) \sin(\Theta_1 - \Theta 3)\cos(\Theta 1 - \Theta 3)$$

$$c_{132} = c_{312} = \frac{1}{2}\frac{\partial d_{23}}{\partial \Theta_1} = (I_{xx3} - I_{yy3})\ \sin(\Theta_1 - \Theta_3)\cos(\Theta_1 - \Theta_3)$$

$$c_{222} = \frac{1}{2}\frac{\partial d_{22}}{\partial \Theta_2} = (I_{yy2} - I_{xx2}) \sin(\Theta_1 - \Theta_2)\cos(\Theta_1 - \Theta_2)$$

$$c_{232} = c_{322} = \frac{1}{2}\frac{\partial d_{22}}{\partial \Theta_3} = (I_{yy3} - I_{xx3})\ \sin(\Theta_1 - \Theta_3)\cos(\Theta_1 - \Theta_3) - m_3 a_2 l_{c3} sin\Theta_3$$

$$c_{332} = \frac{\partial d_{23}}{\partial \Theta_3} - \frac{1}{2}\frac{\partial d_{33}}{\partial \Theta_2} = 2(I_{yy3} - I_{xx3}) \sin(\Theta_1 - \Theta_3)\cos(\Theta_1 - \Theta_3) - m_3 a_2 l_{c3} sin\Theta_3 + I_{xx}\ \sin(\Theta_1 - \Theta_2)\cos(\Theta_1 - \Theta_2)$$

$$c_{113} = -\frac{1}{2}\frac{\partial d_{11}}{\partial \Theta_3} = \frac{1}{2}\, m_3 l_{c3} \sin(\Theta_2 + \Theta_3)$$

$$c_{123} = c_{213} = \frac{1}{2}\frac{\partial d_{32}}{\partial \Theta_1} = (I_{xx3} - I_{yy3})\ \sin(\Theta_1 - \Theta_3)\cos(\Theta_1 - \Theta_3)$$

$$c_{133} = c_{313} = \frac{1}{2}\frac{\partial d_{33}}{\partial \Theta_1} = (I_{xx3} - I_{yy3})\ \sin(\Theta_1 - \Theta_3)\cos(\Theta_1 - \Theta_3)$$

$c_{223} = -\frac{1}{2}\frac{\partial d_{22}}{\partial \Theta_3} = (I_{xx3} - I_{yy3})\ \sin(\Theta_1 - \Theta_3)\cos(\Theta_1 - \Theta_3) +\ m_3 a_2 l_{c3} sin\Theta_3$

$c_{233} = c_{323} =$ - $I_{xx3}\ \sin(\Theta_1 - \Theta_3)\cos(\Theta_1 - \Theta_3)$

Next, the potential energy of the manipulator is just the sum of those of the three links. For each, the potential energy is just its mass multiplied by the gravitational acceleration and the height of its center of mass. Thus

$$P_1 = m_1 \mathrm{g} l_{c1} \tag{4.13}$$

$$P_2 = m_2 \mathrm{g}(d_1 + l_{c2}\, sin\Theta_2) \tag{4.14}$$

$$P_3\ = m_3 \mathrm{g}(d_1 + a_2 sin\Theta_2 + l_{c3}\sin(\Theta_2 + \Theta_3)) \tag{4.15}$$

And so the total potential energy is

$$P = P_1 + P_2 + P_3$$

$$P = m_1 \mathrm{g} l_{c1} + m_2 \mathrm{g}(d_1 + l_{c2}\, sin\Theta_2) + m_3 \mathrm{g}(d_1 + a_2 sin\Theta_2 + l_{c3}\sin(\Theta_2 + \Theta_3)) \tag{4.16}$$

Therefore, the function g_k defined in Equation (4.4) become

$$g_1 =\ \frac{\partial p}{\partial \Theta_1} = 0 \tag{4.17}$$

$$g_2 =\ \frac{\partial p}{\partial \Theta_2} = m_2 \mathrm{g} l_{c2}\ \cos\Theta_2 + m_3 \mathrm{g}(a_2\cos\Theta_2 + l_{c3}\cos(\Theta_2 + \Theta_3)) \tag{4.18}$$

$$g_3 = \frac{\partial p}{\partial \Theta_3}\ = m_3 \mathrm{g}\, l_{c3}\cos(\Theta_2 + \Theta_3) \tag{4.19}$$

Finally we can write down the dynamical equations of the system as in Equation (4.1), Substituting for the various quantities in this equation and omitting zero terms leads to

$$\tau_1 = \ddot{\theta}_1 + (c_{121} + c_{211})\dot{\theta}_1\dot{\theta}_2 + (c_{131} + c_{311})\dot{\theta}_1\dot{\theta}_2 + (c_{231} + c_{321})\dot{\theta}_2\dot{\theta}_3 + c_{212}\dot{\theta}_2^2 + c_{331}\dot{\theta}_3^2\ +\ b_1\dot{\theta}_1 \tag{4.20}$$

$$\tau_2 = d_{22}\ddot{\theta}_2 + d_{23}\ddot{\theta}_3 +\ (c_{122} + c_{212})\dot{\theta}_1\dot{\theta}_2 + (c_{132} + c_{312})\dot{\theta}_1\dot{\theta}_3 + (c_{232} + c_{322})\dot{\theta}_2\dot{\theta}_3 + c_{112}\dot{\theta}_1^2 + c_{222}\dot{\theta}_2^2 + c_{332}\dot{\theta}_3^2 + m_2 g l_{c2}\cos\theta_2 + m_3 g(a_2\cos\theta_2 + l_{c3}\cos(\theta_2 + \theta_3)) +\ b_2\dot{\theta}_2 \tag{4.21}$$

$$\tau_3 = d_{32}\ddot{\theta}_2 + d_{33}\ddot{\theta}_3 + (c_{123} + c_{213})\dot{\theta}_1\dot{\theta}_2 + (c_{133} + c_{313})\dot{\theta}_1\dot{\theta}_3 + (c_{233} + c_{323})\dot{\theta}_2\dot{\theta}_3 + c_{113}\dot{\theta}_1^2 + c_{223}\dot{\theta}_2^2 + c_{333}\dot{\theta}_3^2 + m_3 g l_{c3}\cos(\theta_2 + \theta_3) + b_3\dot{\theta}_3 \quad (4.22)$$

Where b_i is the coefficient of viscous damping for each joint, and $\ddot{\theta}_i$,$\dot{\theta}_i$, and θ_i, comes from the trajectory equation which derive in chapter 3.

4.3 Testing model

In this section we introduce a testing of a model we constructed in a previous section to make sure that we are probably modeling it. This testing will depend on Matlab software to simulate the equations of motion with cubic polynomial trajectories for four cases.*

First case

When the manipulator at home position and it doesn't move, thus, we calculate the torque at each joint that make the robot in static equilibrium.

The torque produced by *joint 1*

$$T_1=0 \quad (4.23)$$

torque produced by *joint 2*

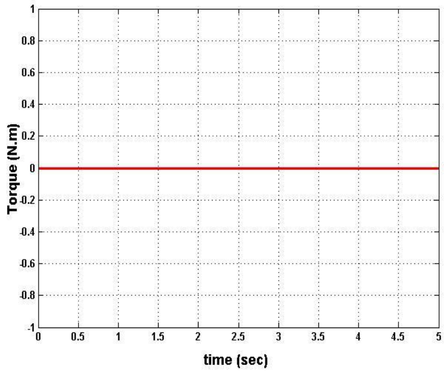
$$T_2= m_2 g l_{c2} cos\Theta_2 + m_2 g(a_2 + l_{c3} \cos \Theta_3)= 3.5\ N.m \quad (4.24)$$

torque produced by *joint 3*

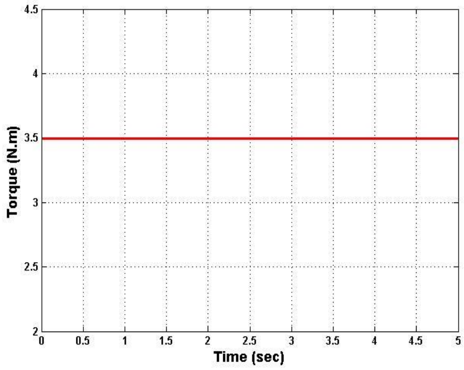
$$T_3= m_3 g l_{c3} cos\Theta_3= 0.7\ N.m \quad (4.25)$$

The torques produced on joint 1,2, and 3 according to simulation are shown in Figure(4.2), and they are matching with the torques we calculated in Equations (4.23), (4.24), and (4.25)

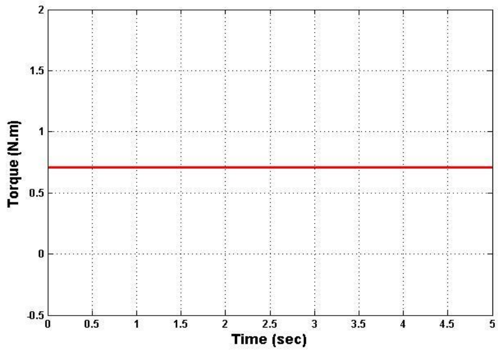
The Matlab script for the dynamic equations is shown in Appendex A.



(a)



(b)

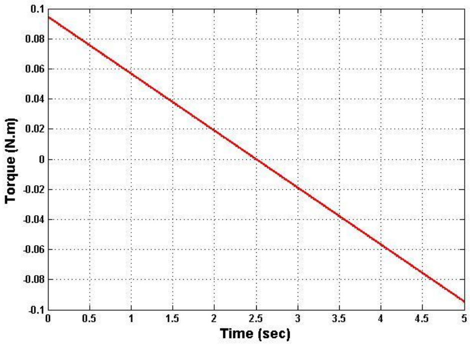


(c)

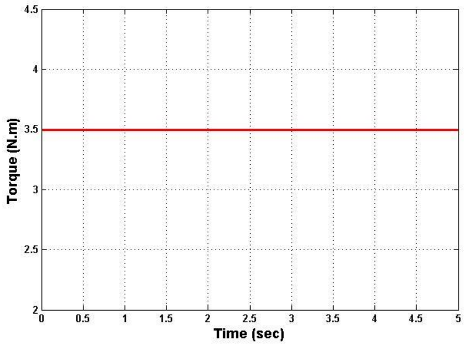
Figure 4.2: Simulation for case one (a) joint 1 (b) joint2 (c) joint 3

Second case

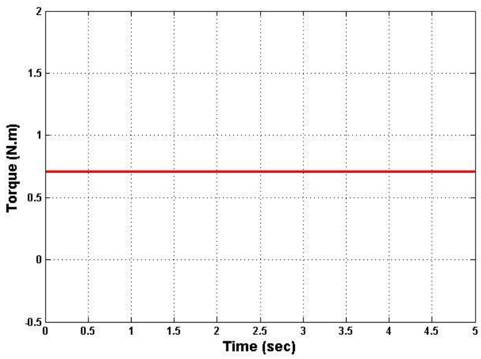
Link 1 is moving from 0-90^0 while the remaining links are not moving, thus, there is no torque acting on joint 2 and joint 3 unless the torque due to static equilibrium, the torque produced by joint 1 is shown in Figure (4.3) and it's like acceleration profile for cubic polynomial trajectory.



(a)



(b)

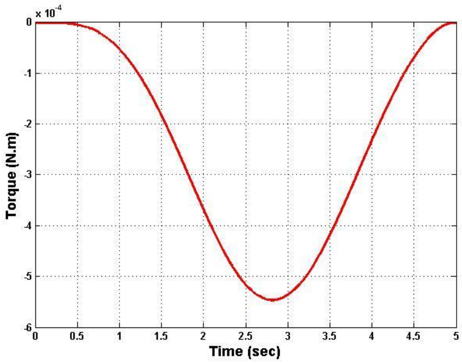


(c)

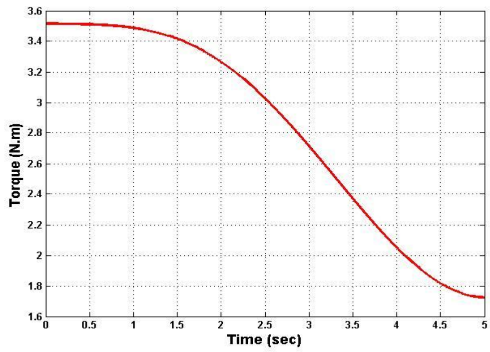
Figure 4.3: Simulation for case two (a) joint 1 (b) joint2 (c) joint 3

Third case

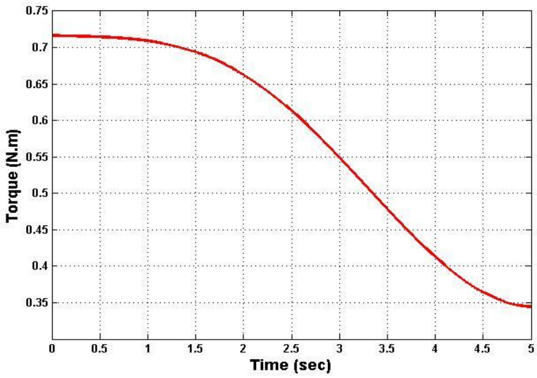
Link 2 is moving from 0-60^0 , while link 1 and link 3 are not moving , in this case the torque produced by joint 3 is starting from high level and end at low level, this happened because the force due gravity become closer to joint 2 ,thus, the torque become less , and this what happened in joint 3. The only force acting on joint 1 is the Coriolis force. This case is shown in Figure (4.4) for each joint.



(a)



(b)

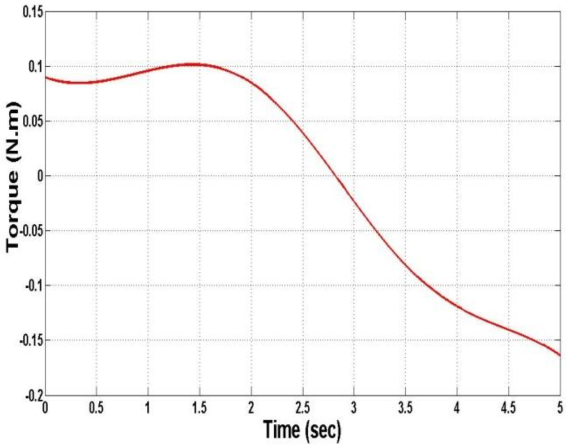


(c)

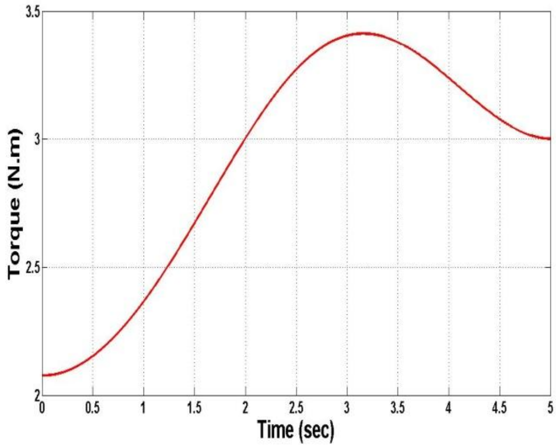
Figure 4.4: Simulation for case three (a) joint 1 (b) joint2 (c) joint 3

Fourth case

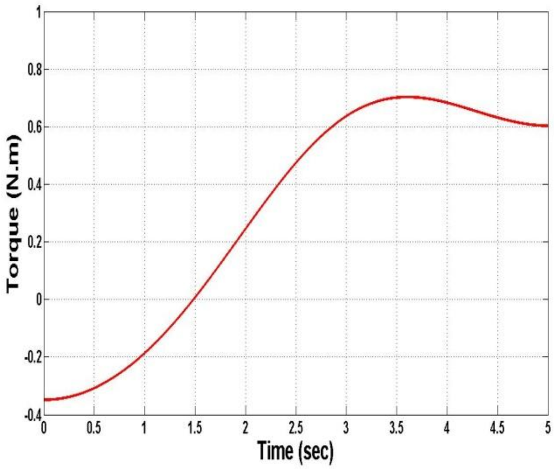
When all joints move to cover the full range of there domain, the resultant torque for each joint is shown in Figure 4.5, these torques are used to select the actuator for each joint.



(a)



(b)



(c)

Figure 4.5: The corresponding torque for case 4 (a) Joint1 (b) Joint2 (c) Joint3

The torques for the joints can be plot in a single graph as illustrated in figure 4.6

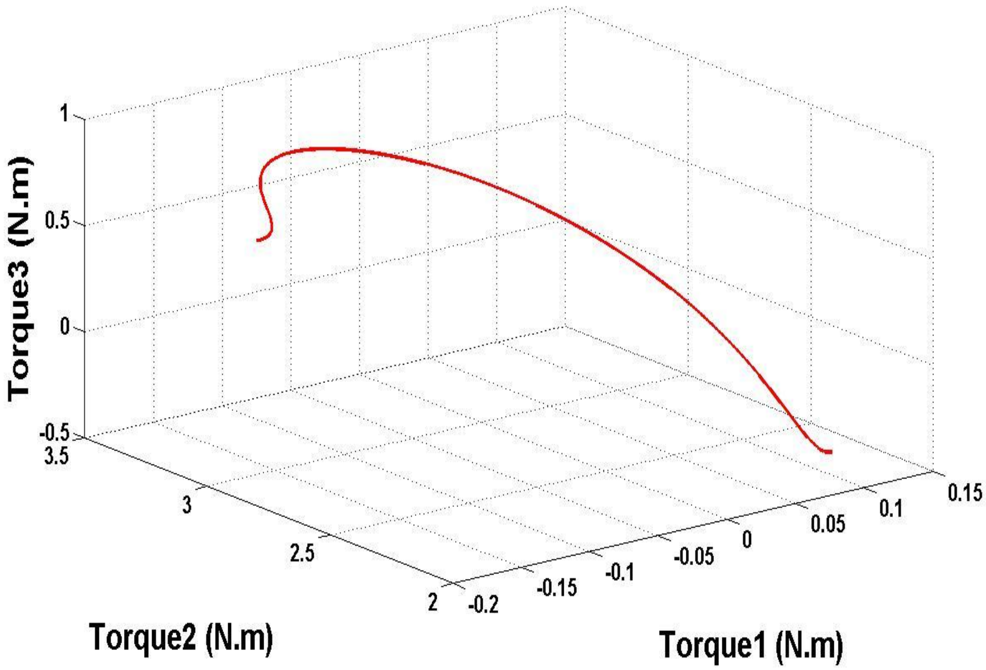


Figure 4.5: The torque for each joint for case 4

Chapter 5
Control Design

5.1 Introduction

Robot control is the spine of robotics. It consists in studying how to make a robot manipulator execute the desired tasks automatically. Typically, robot controller take the form of an equation or an algorithm which is realized via specialized computer programs (Matlab in our case).[5] Robot controllers form part so-called robot control system which is physically constituted of a computer, a data acquisition unit, actuators, the robot itself and some extra "electronics" as illustrated in Figure 5.1. In this chapter we will go deep in these details and explain how the overall system works.

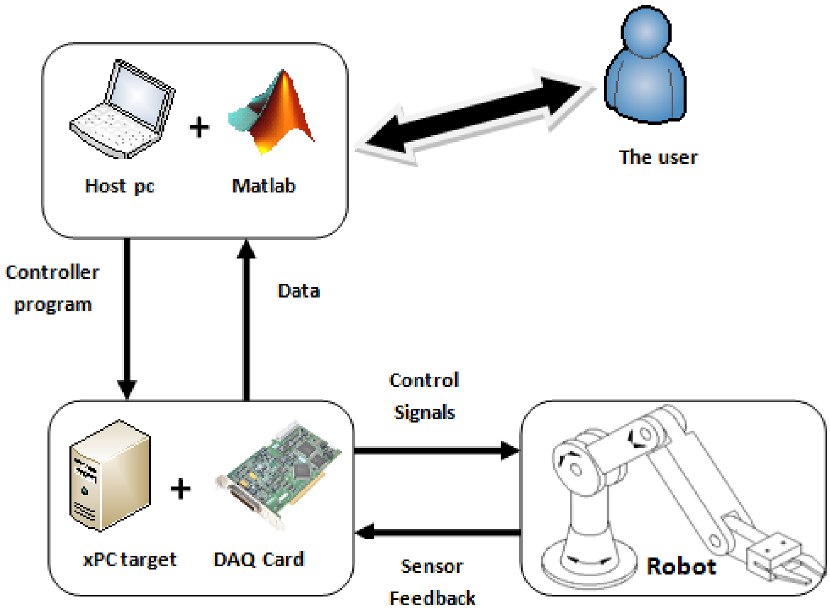


Figure 5.1: The robot control system

5.2 System Architecture

The following subsections consider the system architecture concerning physical description, functional description, hydraulic description, electrical description, and electrical circuit for manual control.

5.2.1 Physical description

The primary function of this robot is to pick an object, moves it to another location, and release it. The construction of the hydraulic arm resembles a typical three-link, articulated robot arm with three revolute joint and gripper end effector. Each arm link is fitted with a hydraulic rotary actuator with limited rotation. Figure 5.2 shows this type of rotary actuator.

• The first revolute joint affects hydraulic arm rotation about an axis that is perpendicular to the table (east-west base rotation). The angle of rotation of this link is 180^o, from -67^o to $+113^o$ relative to the base frame.

• The second revolute joint affects overall angle of the arm relative to the reference coordinates (north-south shoulder rotation). The angle of rotation of this link is 90^o, from -45^o to $+45^o$ relative to the shoulder frame.

• The third revolute joint affects the amount of arm extension (elbow movement). The angle of rotation of this link is 90^o, from 0^o to -90^o relative to the elbow frame.

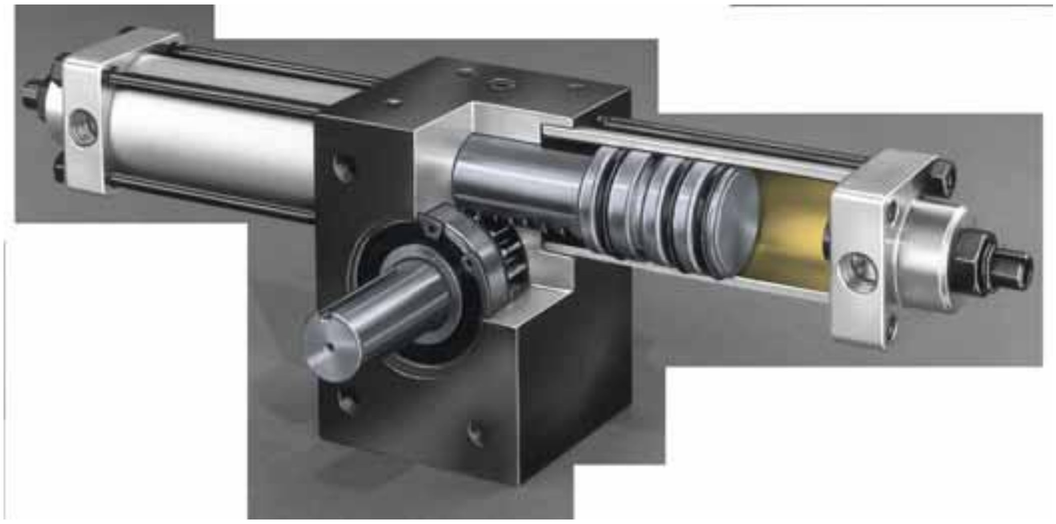


Figure 5.2: Hydraulic rotary actuator

5.2.2 Functional description

The user can operate the machine manually or by using computer in order to achieve the desired functionality. The user may select from two distinct modes of operation: manual control or closed-loop computer control. Manual control refers to user input routed directly to the valve system for joints control (manual control). The user input is directly related to the flow demand that is routed to the valve system, and therefore the user has direct control over movement of the system. The term closed-loop control refers to the system managing the flow demand routed to the valve system to achieve the desired movement or desired position. This operation can be done by using computer.

5.2.3 Hydraulic description

The system uses a vented hydraulic reservoir at atmospheric pressure. Hydraulic flow is generated by a fixed displacement hydraulic pump driven by electric motor. A pressure relief valve is fitted to the output side of the hydraulic pump in order to control maximum system pressure by providing a regulated flow path back to the reservoir. The primary hydraulic flow path is from the pump to the proportional control valve that controls the overall flow of the system. The electrically actuated solenoid valves are using for control the direction of rotation of each joint (on\ off control). A hydraulic schematic of the system is shown in Figure 5.3.

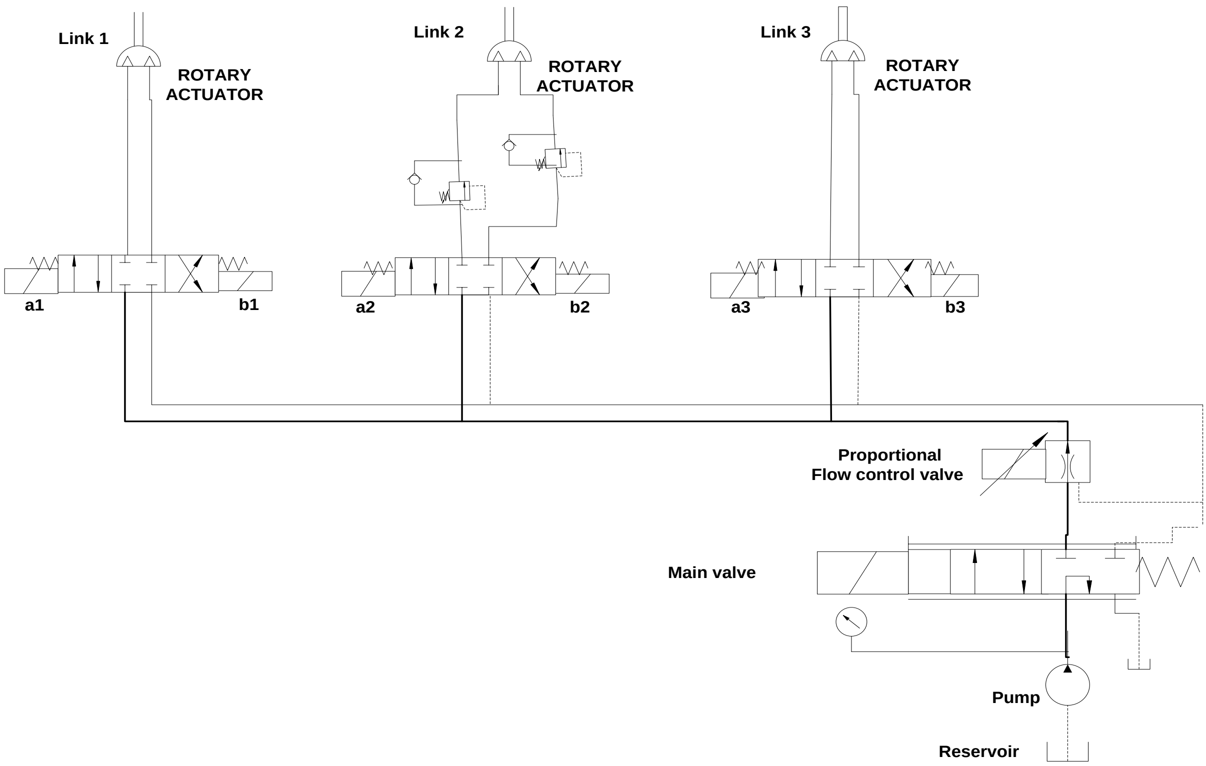


Figure 5.3: Hydraulic schematic of the work circuit

5.2.4 Electrical description

The machine is powered by 220 volt AC power. Incoming AC power is routed in parallel to the hydraulic pump electric motor, main valve and to the DC power supply. The power supply ensures that system voltage is regulated to 24 volts DC. The system voltage is routed through an emergency power shutoff switch to DC power supply, toggle switches and system electronic unit. A simplified electrical circuit for 220 volt AC power supply is shown in Figure 5.4.

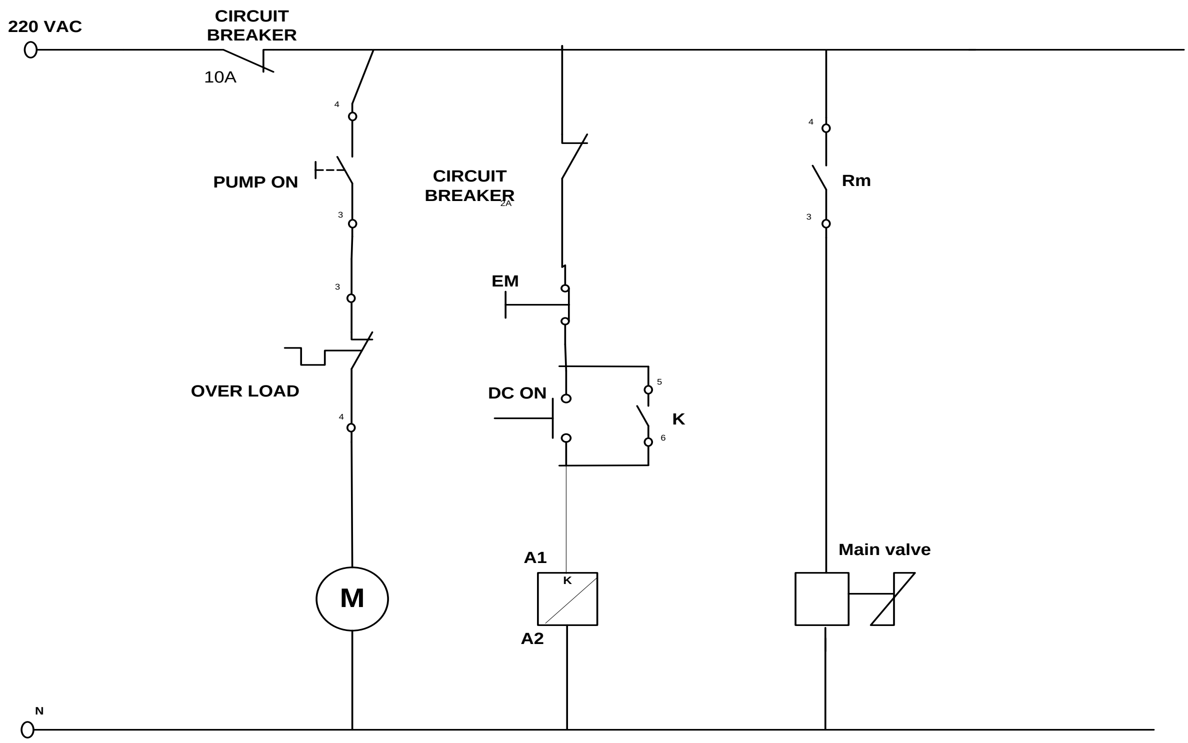


Figure5.4: A simplified electrical circuit for 220 volt AC power supply

5.2.5 Electrical circuit for manual control

As we said before, there are two modes of operation; in manual control mode the user has direct control over movement of the system. In order to do that, two electrically actuated solenoid valves are using for each rotary actuator; one solenoid used for clockwise (CW) direction and the other is used for counter clockwise (CCW) direction. Each solenoid is powered by 24 volt DC power supply. In order to activate each direction with one signal by toggle switch we used two normally open relays for each solenoid. Figure 5.5 shows the electrical circuit for open-loop control.

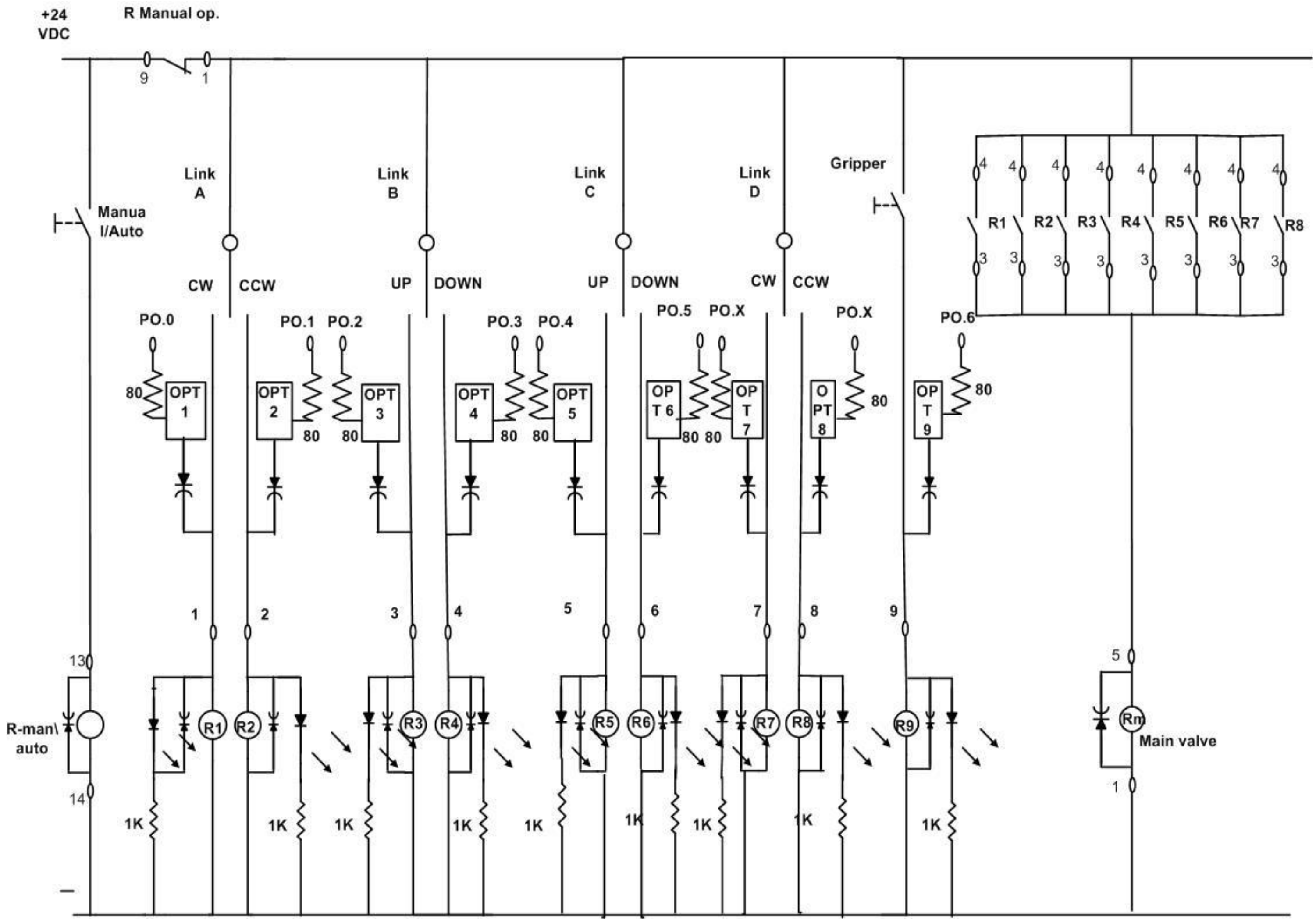


Figure5.5: Electrical circuit for open-loop control.

The main valve will be activated if any solenoids activate, which allow the oil to flow to the system and active the actuators.

The mode of operation can be selected through a switch which indeed gives a signal to a normally closed relay; if the switch open then the manual control mode will activate, and if it closes then the closed loop control mode will activate as illustrated in Figure5.5.

The amount of overall flow can be controlled by proportional valve, and we can control it through analog signal, this signal is a voltage signal (0-10 volt), it can be controlled manually or by using computer, in manually controlled signal we used 10kΩ potentiometer to change the analog voltage signal from (0-10 volt), this 10volt signal can be taken from 24 DC voltage source by using regulator (TS 7810). As illustrated in Figure5.6. The computer controlled signal will be discussed in the following sections.

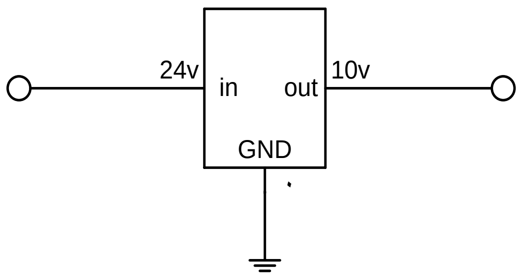


Figure 5.6: Regulator circuit

5.3 Closed-loop control

The term closed-loop control refers to the robot system managing the flow demand routed to the valve system to achieve the desired movement or desired position with smooth motion, and using sensors that give a feedback read for the final position for each link angle. We used the computer for this operation; in order to interface this robot with the computer we use Data Acquisition Card (DAQ Card) with the following features:

1. One Analog output to control the flow through proportional valve
2. Three analog input to read the position for each link through potentiometer
3. Seven digital output; each output is connected to each solenoid to give a signal for desired motion.

To achieve these specification we used for this job the" National Instrument 6024E DAQ Card". Figure5.7 shows this type of DAQ card.

Figure 5.7: National Instrument 6024E DAQ Card

The DAQ digital output signal used for each solenoid is 5 volt signal; this signal can't activate the 24v relays directly, we used optocoupler to active the relay with 5 volt and low current signal, the choice of optocoupler has an advantage in isolated the reverse signal come back to the DAQ card. The optocoupler we use is (CNY17).

The interfacing circuit between digital outputs from the DAQ card and the solenoid valve relays is shown in Figure 5.8. The resistances in this figure used to make sure that the maximum current from the DAQ not exceed 100mA, we used 80Ώ resistance to achieve this purpose. The diodes shown in the circuit are used to prevent reverse current to come back to the optocoupler in manual mode, the numbers appear at the end of each diodes are related to the relays as illustrated in Figure 5.5.

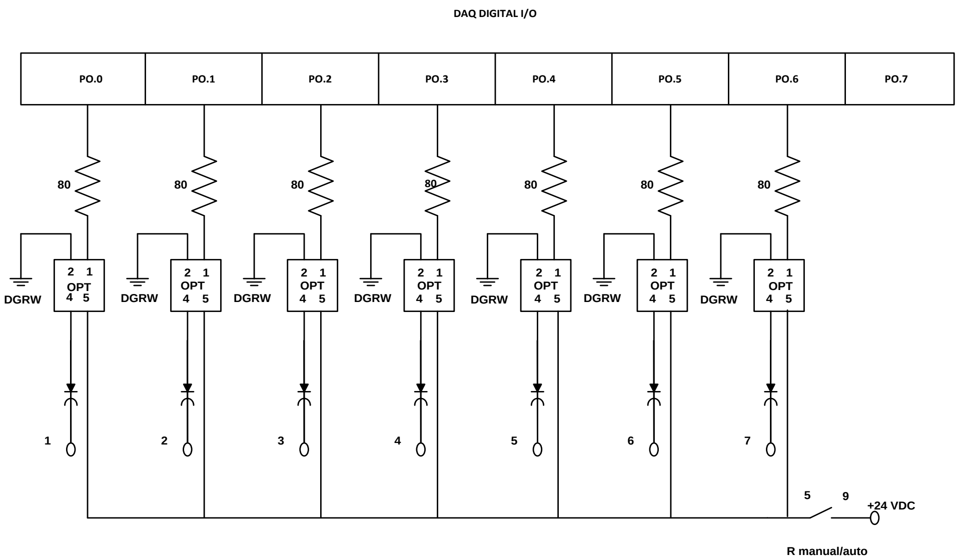


Figure 5.8: The interfacing circuit between digital outputs from the DAQ card and the solenoid valve relays

As we said before, the amount of overall flow can be controlled by proportional valve through analog signal (0-10 volt), this signal can be change manually as we discussed before, or by using computer. The signal from computer come from the Analog output port from the DAQ Card, the analog output voltage from the DAQ card is (from -10 to 10 volt), this signal can be used to control the flow through the proportional valve. Figure 5.9 shows the circuit that controls the proportional valve manually or from the analog signal from the DAQ Card.

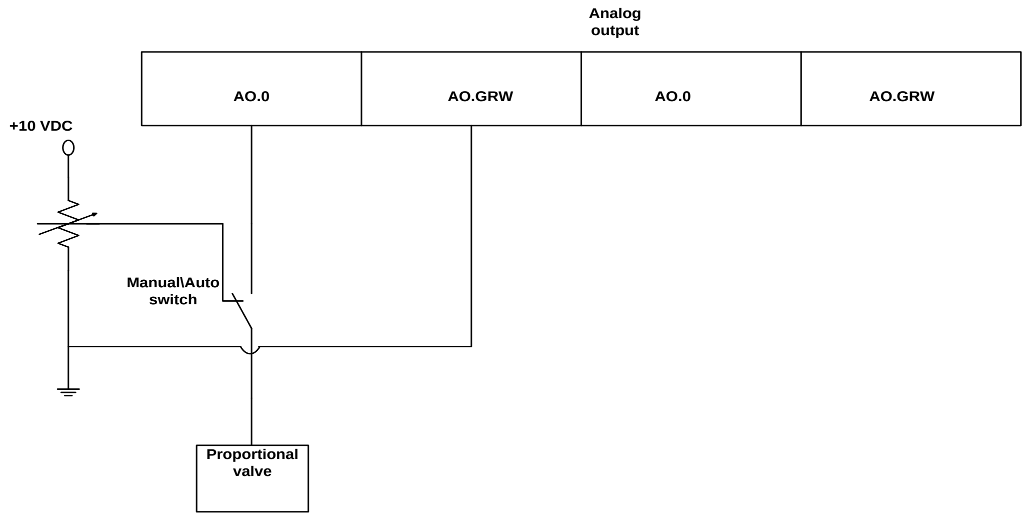


Figure 5.9: Manually and automatically control circuit of the proportional valve

5.3.1 Feedback sensors

In a closed-loop control system, three sensors monitor the system output (Joint angles) and feed the data to a controller which adjusts the control (the joint angle) as necessary to maintain the desired system output (match the desired position which is x, y, and z coordinate of the end-effecter). This robot uses potentiometers to determine where it is and then controls their joints to match the desired position. The output from the potentiometer is an analog voltage that is proportional to the angle of rotation for each joint. These analog signals are connecting to the analog input of the DAQ card.

5.3.2 Potentiometer Calibration

In order to represent the angle for each link with a voltage signal, we calibrated the potentiometers attach to each link. The potentiometer output voltage for each joint represent the angle of that joint, our purpose in this section is to find the formula that represent the joint angle with analog voltage.

For the first link, we found that the angle (θ_1) change (from -67^o to 113^o) and the voltage change (from 3.5 to 9 volt), we construct a linear relation between them as shown in Figure 5.10.

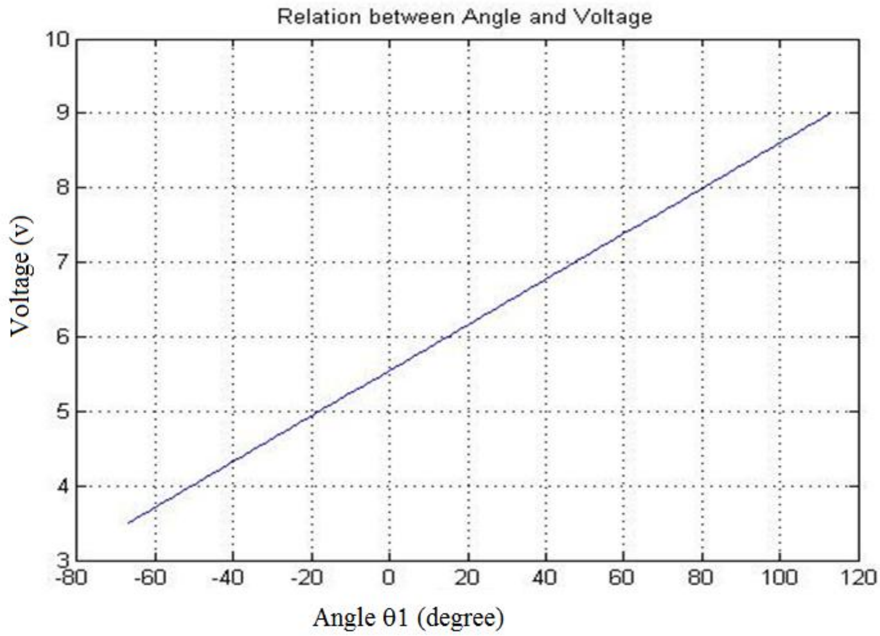


Figure5.10: Relation between voltage and angle for the first link

From this figure we found the formula for angle to voltage representation using Matlab software, the corresponding formula is:

$$\mathbf{V_1 = 0.03056\ \Theta_1 + 5.547}$$

For the second link, we found that the angle (θ_2) change (from 45^o to -45o) and the voltage change (from 9 to 1 volt), We construct a linear relation between them as shown in Figure 5.11.

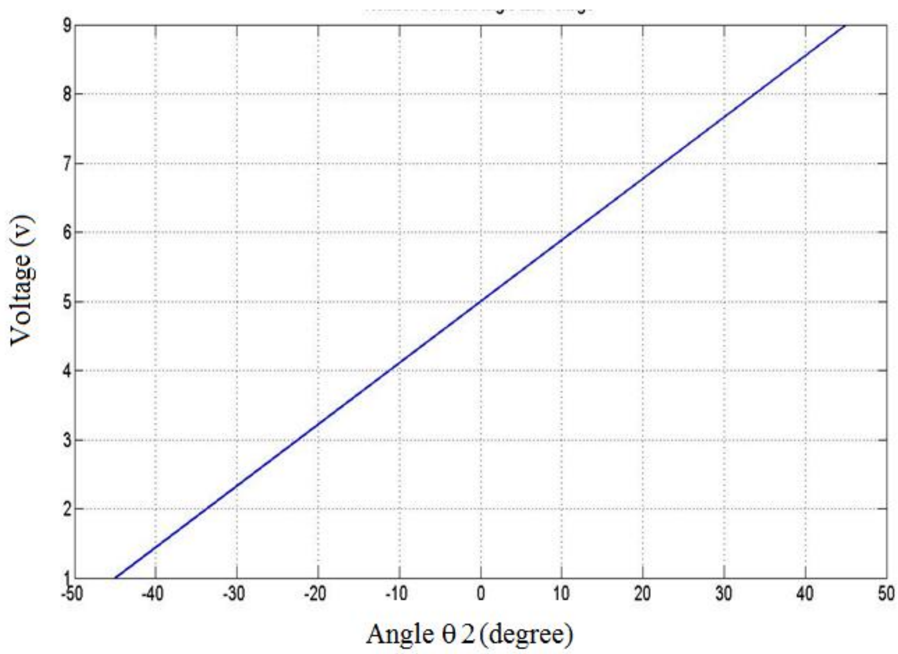


Figure5.11: Relation between voltage and angle for the second link

From this figure we found the formula for angle to voltage representation using Matlab software, the corresponding formula is:

$$\mathbf{V_2 = 0.08889\ \Theta_2 + 5}$$

For the third link, we found that the angle (θ_3) change (from -45^o to -135^o) and the voltage change (from 1 to 9 volt), We construct a linear relation between them as shown in Figure 5.12.

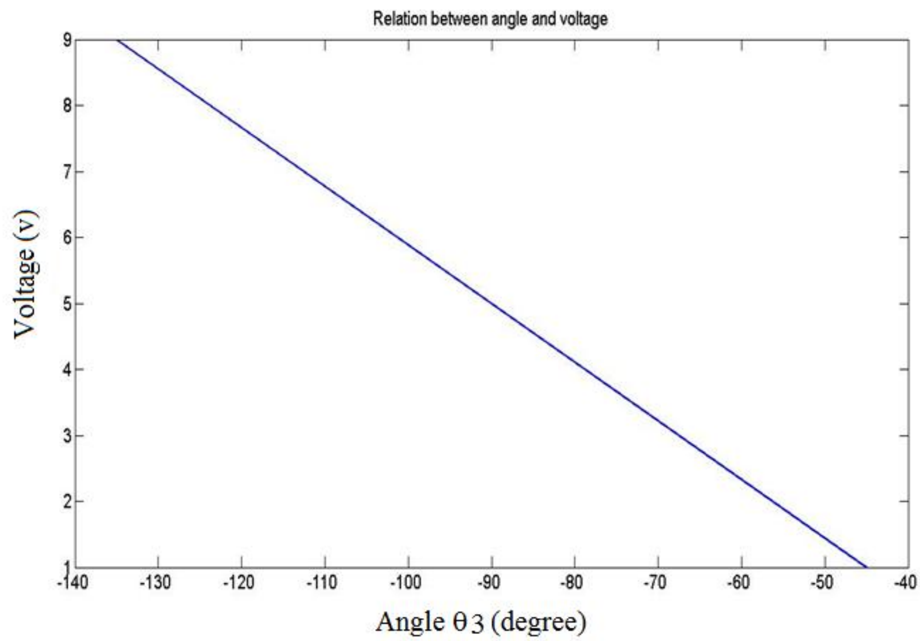


Figure5.12: Relation between voltage and angle for the third link

From this figure we found the formula for angle to voltage representation using Matlab software, the corresponding formula is:

$$\mathbf{V_3 = -0.08889\Theta_3 - 3}$$

5.3.3 xPC Target

We mount the DAQ card on the xPC Target which allows the target PC system to work independently of a host PC. This independence is achieved by automatically loading and running the real-time kernel and application on power up.

Why we use xPC Target?

xPC Target is a high performance host-target prototyping environment that enables you to connect your Simulink® and Stateflow® models to physical systems and execute them in real time on PC-compatible hardware. xPC Target is ideal for rapid controller prototyping and hardware-in-the-loop simulation of control and data processing systems. It enables you to add I/O blocks to your models, automatically generate code with Real-Time Workshop®, and download the code to a second PC running the xPC Target real-time kernel.

xPC Target lets you use your Simulink and Stateflow models further into your design process by:

• Providing real-time target and I/O capabilities on any PC-compatible system

• Eliminating the need to customize or write any code

5.3.4 Controllers and software

After we prepare all electrical connections and interfacing circuits for the robot, we interested in solving motion control problem. In motion control problem, the manipulator moves to a position to pick up an object, transports that object to another location, and deposits it. We treat this problem in the joint space.

5.3.4.1 Joint space control

The main goal of the joint space control is to design a feedback controller such that the joint coordinates track the desired motion as closely as possible. The control of robot manipulators is naturally achieved in the joint space, since the control inputs are the joint torques.

Figure 5.13 shows the basic outline of the joint space control methods. Firstly, the desired motion, which is described in terms of end-effector coordinates, is converted to a corresponding joint trajectory using the inverse kinematics of the manipulator. Then the feedback controller determines the joint torque necessary to move the manipulator along the desired trajectory specified in joint coordinates starting from measurements of the current joint states.

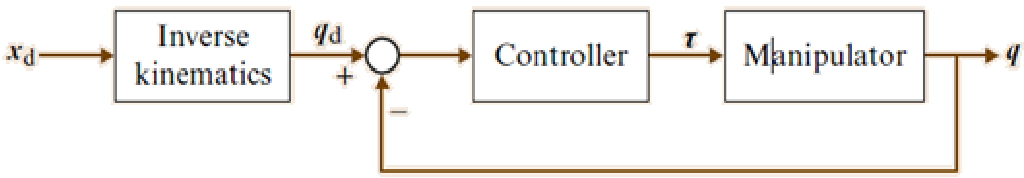


Figure 5.13: Generic concept of joint space control

5.3.4.2 Independent joint control

We adapt independent joint control to control the robot manipulator. By independent-joint control (i.e., decentralized control), we mean that the control inputs of each joint only depends on the measurement of the corresponding joint displacement and velocity. Due to its simple structure, this kind of control schemes offers many advantages. For example, by using independent-joint control, communication among different joints is saved. Moreover, since the computational load of controllers may be reduced, only low-cost hardware is required in actual implementations. Finally, independent-joint control has the feature of scalability, since the controllers on all the joints have the same formulation.[6]

The simplest independent-joint control strategy is to control each joint axis as a single-input single-output (SISO) system; this type of control appears in Figure 5.14. This figure is common for all links.

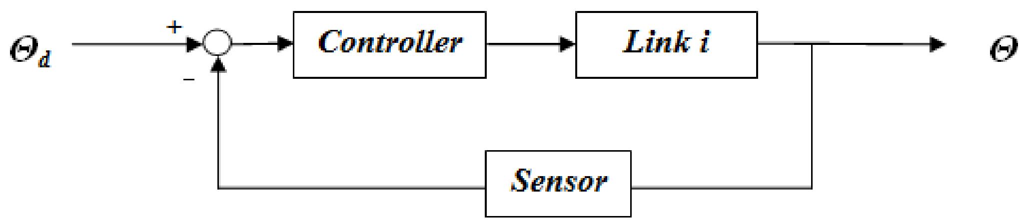


Figure 5.14: Independent joint control scheme

Because the electrically actuated solenoid valves which using for control the actuators is (on\ off control). Then we can’t control the velocity for each joint independently by this method, as mentioned before, there is one proportional valve to control the overall flow and thus the velocity for all links, this leads to seek for a method to control all links velocity with a common controller, this controller principle depends on the control of the norm of the error.

5.3.4.3 Least norm solution

The norm controller depends on weighted the error goes to each link, and allow the system to control the flow and therefore the velocity of all joints, the idea of norm controller of the error relies that if there is an error command on at least one joint, then the norm weighted it and allow the controller to control the amount of flow through the proportional valve, this operation emphasized that the velocity of the joints will decrease when the robot closes to its target position. Figure5.15 shows the principle of norm controller.

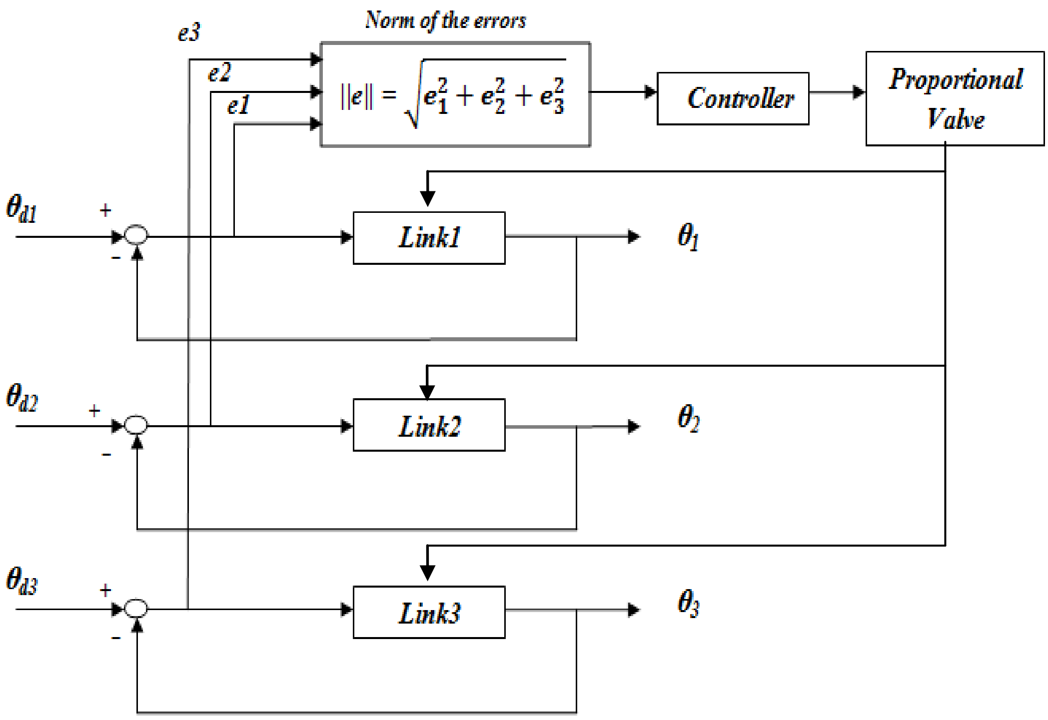


Figure 5.15: The principle of norm controller

The signal out from the norm block enters to the controller block, out from it, and then goes to the proportional valve. In order to find the controller, and since we don't know the transfer function for the proportional valve, we used the experiments depend on Hardware-in-Loop simulation to find the formulation of the controllers.

We assume PD controller, and changing the parameters until we achieve a smooth response. The PD controller we achieved with a smooth response has the following formulation:

PD Controller: $G_c(s) = 2 + s$

The Matlab Simulink model for the Robot is shown in Figure 5.16.

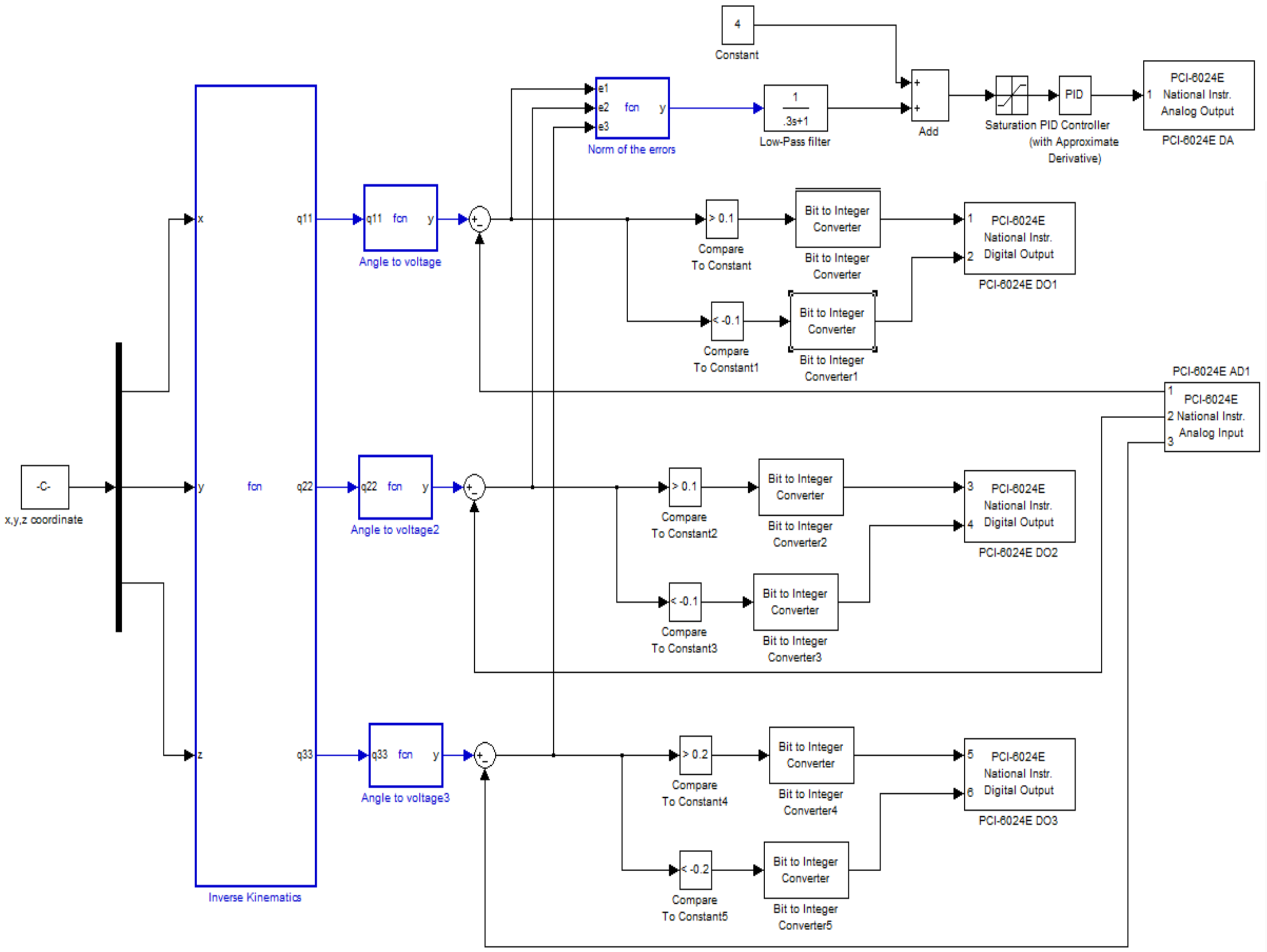


Figure5.16: Simulink model for the robot

From Figure 5.16. the signal that's go to the proportional valve is added to some constant value to insure that the flow will not reach to zero. The filter used in this model is a low pass filter, aimed to eliminate the undesired signal(noise) comes from the feedback sensors.

In Simulink model shown in Figure 5.16 we compare the error signal goes to each link with the value close to zero(because the error signal cant reach exactly to zero) to select the direction of motion(CCW or CW). If the error more than zero then the joint rotate in CCW direction, and if it is less than zero then the joint rotate in CW direction.

Chapter 6
Experimentations and Results

6.1 Introduction

This chapter contains the results that are obtained from the experiments which are done to verify the theoretical results reached in the previous chapters, where the mechanical, electrical, and control designs are to be applied in this practical side. The practical results and modifications that are to the theoretical results are discussed.

6.2 Response testing of control system

MATLAB and SIMULINK in addition to xPC Target are used to simulate and evaluate the performance of the proposed controller that applied on the robot. The type of controller is PD controller applied to the norm of the error to control the robot arm using an independent joint control mechanism. The purpose of this controller is to improve the performance of the robot arm to acquire the desired tasks.

In order to assess the efficacy of the proposed controller, simulation studies have been conducted to check the efficiency of the system PD controller, this test depend on check the response of each joint to step reference independently.

Figure 6.1, Figure 6.2 and Figure 6.3 show the output response of the joints of the robot using PD controller.

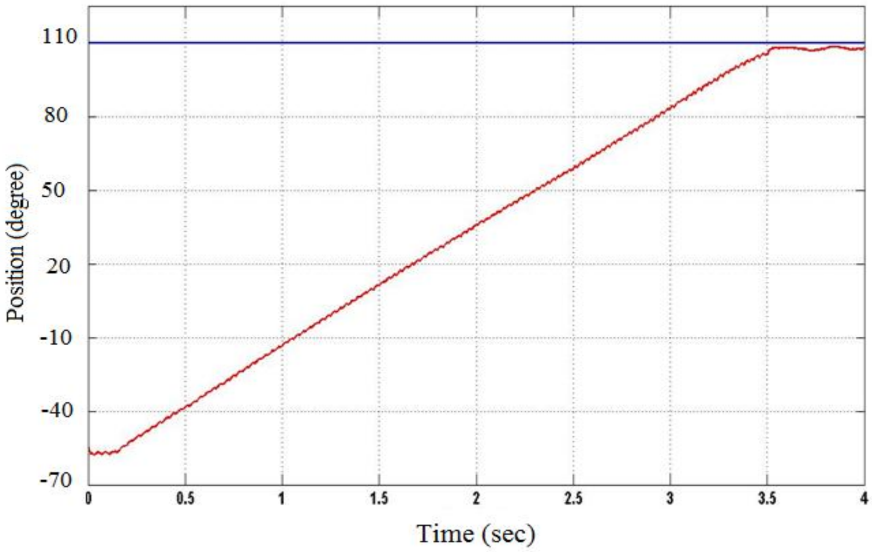


Figure 6.1: Step response for the first joint

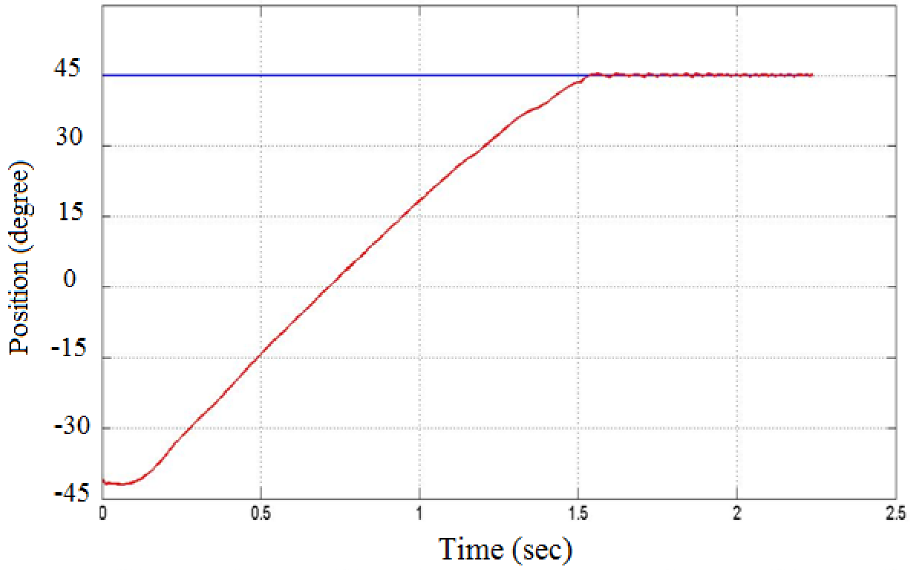


Figure 6.2: Step response for the second joint

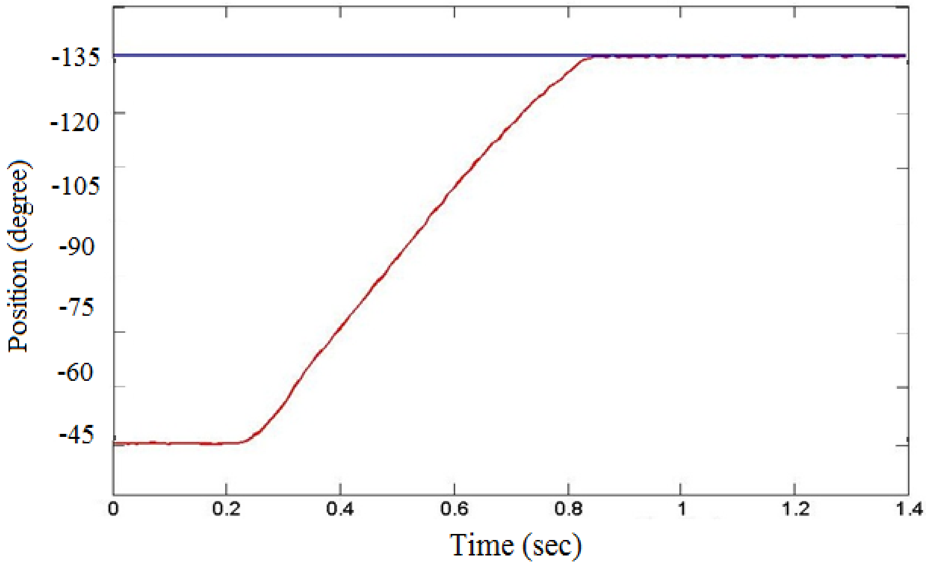


Figure 6.3: Step response for the third joint

We note from the previous figures that the response for each link to a step reference is fine. For the first link, the response has approximately negligible steady state error, there is no overshoot and the settling time is acceptable. While in the second and third links the steady state error is close to zero, no overshoot appeared, and the settling time is also acceptable.

6.3 Accuracy and Repeatability Testing

One of the most important specifications associated with a robot manipulator is repeatability; it described the closeness of the agreement occurring between the results obtained for quantity when it is measured several times under the same conditions. While the accuracy is the measure of how close the manipulator can come to a given point within its workspace.

We test the repeatability and accuracy of the robot, this test depend on measured the actual value for specific point for 10 times, this point is (-30,30,15), the measured values are listed in the following Table:

Test No.	**Measured values**			**Error in each coordinate**			**Error (cm)**
	x_m	y_m	z_m	$d_x=x-x_m$	$d_y=y-y_m$	$d_z=z-z_m$	$\sqrt{d_x^2+d_y^2+d_z^2}$
1	-30.5	29.5	14.8	0.5	0.5	0.2	0.73
2	-30.7	29.2	15	0.7	0.8	0	1.06
3	-30.5	29.7	16	0.5	0.3	-1	1.15
4	-29	30	15.5	-1	0	-0.5	1.11
5	-30	29	15.5	0	1	-0.5	1.11
6	-29.5	28.8	15	-0.5	1.2	0	1.30
7	-29.8	31	15	-0.2	-1	0	1.019
8	-30	30.5	16	0	-0.5	-1	1.12
9	-30.6	29	15	0.6	1	0	1.166
10	-30.6	29.5	15.2	0.6	0.5	-0.2	0.8

Table 6.1: The error for each measured values

The graph in Figure 6.4 shows the error for each test according to the values in Table6.2. This graph shows the repeatability and accuracy test for this robot and show how the error is changed when the robot return to the same point.

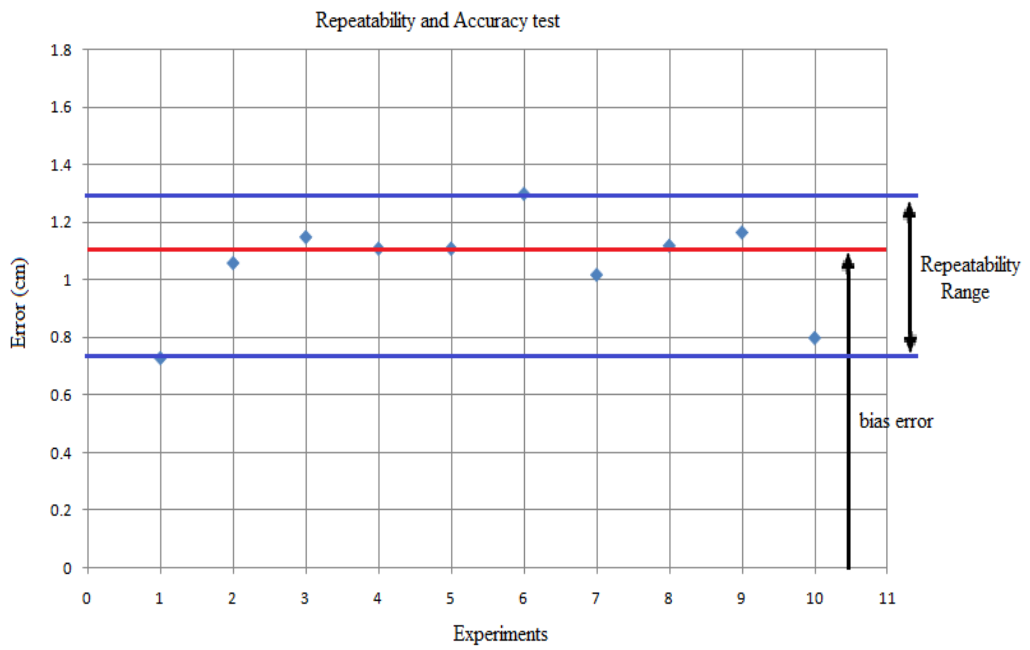


Figure6.4: Repeatability and Accuracy Test for the robot

Form the results we obtained from the repeatability and accuracy test, we conclude that the system is repeatable within a circle of 0.5 cm diameter, and there is a constant error (bias error) in each experiment, this constant error is 1.1 cm, as a result we can say that the system has a repeatability of 0.5cm and accuracy within 1.1 cm.

6.4 Conclusion

Robotics has become recently an interesting area of research. In this project, we study the robot manipulator from two sides: modeling and control. Modeling process includes kinematic and dynamic. This process is important before controlling the robot to save the robot from being damaged. Appling a control technique is important to guarantee high efficiency and lower error for the motion of the robot.

The desired tasks were accomplished using three stages: the first stage was to provide systematic rules for analyzing forward and inverse kinematics solutions for the robot manipulator using DH convention, then analyzing the mathematical model for this robot by using Eular-Lagrange equation. In the third stage, we discussed the problem of control techniques. PD controller was applied to the norm of the error, to control the robot manipulator, ***this method of control used for the first time to control a hydraulic robot manipulator.***

The objective of this controller was to control the robot arm to reach the specified location with minimum error while meeting certain specification. The tracking path from the initial position to the final position which discussed in chapter three was not considered in control problem because the control of the joints is (on/off control).

All simulations and experiments were presented using MATLAB, SIMULINK and xPC Target, which are used widely in control applications.

6.5 Future work

The results of this work can be basic point for future studies. The dynamic model for the robot introduced in chapter 4 can be used to design control algorithm with different hardware and servo system to produce high performance robot arm. Another subject that could be of interest is the method of control; it may be controlled by PLC or microcontroller.

References

[1] M. W. Song, S.Hutchinsons, and M. Vidyasagar, "Robot modeling and control", John Wiley & Sons, Inc, 2006

[2] J.J. Craig, "Introduction to robotics mechanics and control", second edition, Silma, Inc, 1989

[3] B. Siciliano, and O. Khatib, "Springer handbook of robotics", springer-Verlag Berlin Heidlberg, 2008

[4] B. Siciliana, L. Sciavicoo, L. Villani, and G. Oriolo, "Robotics modeling, planning and control", Springer- Verlag London Limited, 2009

[5] R. Kelly, V. Santibáñez and A. Loría "Control of Robot Manipulators in Joint Space", Springer-Verlag London Limited 2005

[6] Andrew J. Smith and Brian Van Batavia, "Electronic Control for Hydraulic Applications", Eaton Corporation, 2008

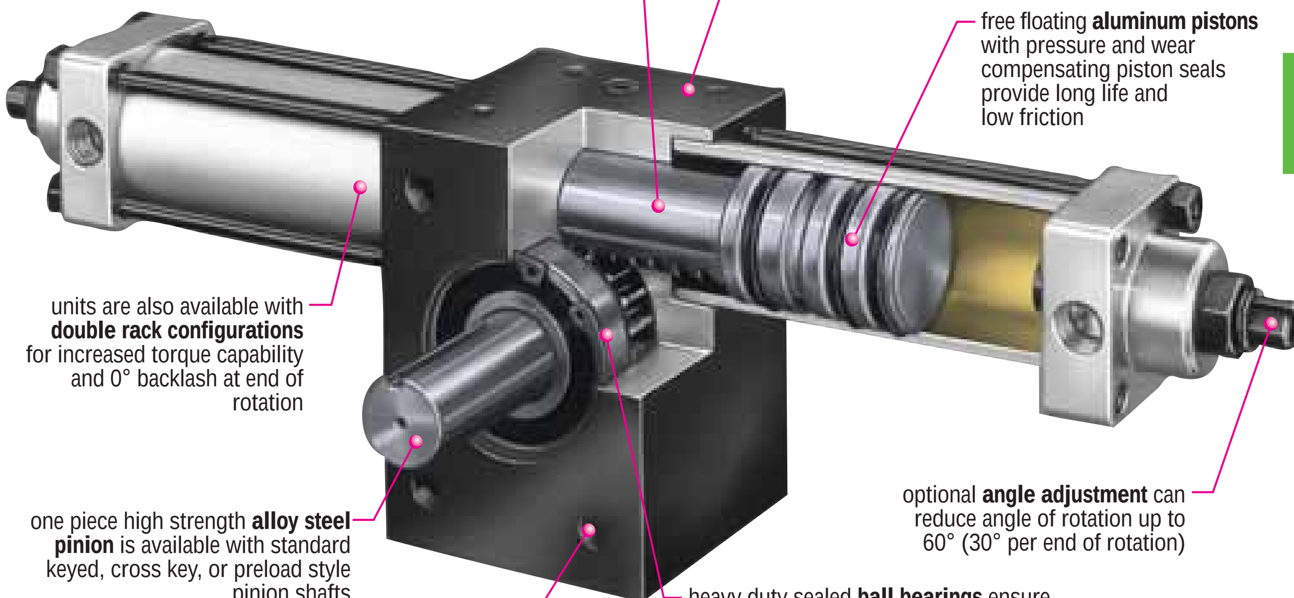
[7] Ahmed Z. Alassar, "Modeling and Control of 5DOF Robot Arm Using Supervisory Control", The Islamic University of Gaza, 2010

Appendices

1000-8000

HEAVY DUTY HIGH TORQUE

OUTPUT TORQUES TO 31,800 in-lb [3595 Nm]



Major Benefits

- Heavy duty
- Wide variety of options and accessories
- Versatile design
- High torque

Industry Uses

- Automotive
- General machine builders

UNITS WITH IMPERIAL SHAFTS AND KEYWAY

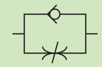
TO ORDER SPECIFY:
Type, Design No., Series, Angle of Rotation, and Options.

R1 1 A 2 180 - P - D - A - K-M-V

DESIGN NO.
1 - Imperial
5 - Metric - Ports and mounting are metric. Pinion shafts and keyway are imperial.
6 - Metric Complete

SERIES
1 (000) 1" Bore Single Rack
2 (000) 1" Bore Double Rack
3 (000) 1-3/8" Bore Single Rack
4 (000) 1-3/8" Bore Double Rack
5 (000) 2" Bore Single Rack
6 (000) 2" Bore Double Rack
7 (000) 3" Bore Single Rack
8 (000) 3" Bore Double Rack

PORT CONTROL©



BUILT-IN METER OUT FLOW CONTROL VALVE
P - Flow control both directions
P1 - Flow control clockwise
P2 - Flow control counterclockwise

ANGLE ADJUSTMENT
A - Angle adjustment both ends
A1 - Angle adjustment clockwise 30°
A2 - Angle adjustment counterclockwise 30° (20° for Series 8000)

TYPE
R1 - Single Shaft
R2 - Double Shaft

FLUID MEDIA
A - Pneumatic
H - Hydraulic

ANGLE OF ROTATION STANDARD ANGLES
45°, 90°, 180°, 270°, 360°, and 450°
For other available rotations, consult PHD.

CUSHION OR SHOCK PAD
D - Cushions both directions
D1 - Cushion clockwise
D2 - Cushion counterclockwise
B - Shock Pads both directions
B1 - Shock Pad clockwise
B2 - Shock Pad counterclockwise

(Cushions and Shock Pads are not available on the same end of actuator. Shock Pads are not available for Hydraulic use.)

STANDARD OPTIONS
E - Magnetic Piston for Solid State Switch
I - Port Position 1 on top rack
Port Position 3 on bottom rack
(Available on Series 2000, 4000, 6000, and 8000 only.)
M - Magnetic Piston for Reed Switch
O - Ports in Position 1
(Available on Series 1000, 3000, 5000, and 7000 only.)
Q - Ports in Position 3
(Available on Series 1000, 3000, 5000, and 7000 only.)
T - Ports in Position 4
V - Fluoro-Elastomer Seals
W - Close Tolerance Rotation, +30 minutes, -0
Z1 - Electroless Nickel Plate

DESIGN NO 1 AND 5 OPTIONS ONLY
C - Cross Key Pinion Shaft
G - Shaft Seal both sides
H - Hollow Pinion Shaft (not available on type R2 units)
J - Hall Sensor for rotations not exceeding 180°
(Set Point Module is ordered separately)
K - Preload Keyway Pinion Shaft (required for use with hub adaptor)
L - Counterclockwise Unidirectional Clutch
(Not available on 7000/8000 units)
N - Pilot Valve Actuator (PVA)
R - Clockwise Unidirectional Clutch
(Not available on 7000/8000 units)
S - SAE Ports (Hydraulic Units Only)

NOTES:
1) Sensor must be used with a PHD Set Point Module. See Switches and Sensors section for information and ordering data.
2) Mounting flanges must be ordered separately.
3) SAE Ports available. Consult PHD for sizes.

Options may affect unit length. See unit dimension and options pages for adders.

PROXIMITY SWITCH MOUNTING BRACKETS

SERIES	SIZE NO.
1000 & 2000	32
3000 & 4000	34
5000 & 6000	38
7000 & 8000	39

See Switches and Sensors section for complete ordering information.

PHD UNLIMITED UNIQUE SOLUTIONS™

UNIQUE ROTARY ACTUATORS ARE AVAILABLE. SEE UNIQUE PRODUCTS AT THE END OF THIS SECTION.

SPECIFICATIONS	SERIES 1000-8000
PNEUMATIC OPERATING PRESSURE	20 to 150 psi [1.4 to 10 bar]
HYDRAULIC OPERATING PRESSURE**	40 to 1500 psi [2.8 to 103 bar]
OPERATING TEMPERATURE	-20° to 180°F [-29° to 82°C]
ROTATIONAL TOLERANCE	Nominal rotation +10° to -0°
BACKLASH AT ANY MID-ROTATION POINT AND AT END OF ROTATION WITHOUT -A (DOUBLE RACK)	1° (2000), 0°30' (4000, 6000), 0°15' (8000)
BACKLASH AT END OF ROTATION WITH -A* (DOUBLE RACK)	0° (2000, 4000, 6000, 8000)
BACKLASH ON ALL SINGLE RACK UNITS (END AND ANY MID-ROTATION)	1° (1000), 0°30' (3000, 5000), 0° 15' (7000)
LUBRICATION	Factory lubricated for rated life
MAINTENANCE	Field repairable

NOTE: *-A angle adjustment screw must be engaged or adjusted to achieve 0° backlash

SIZE	WEIGHT BASE lb	WEIGHT BASE kg	WEIGHT ADDER lb/°	WEIGHT ADDER kg/°	BORE DIAMETER in	BORE DIAMETER mm	DISPLACEMENT VOLUME/DEG in³/°	DISPLACEMENT VOLUME/DEG cm³/°	THEORETICAL TORQUE OUTPUT in-lb/psi	THEORETICAL TORQUE OUTPUT Nm/bar	ROTATIONAL VELOCITY MAX deg/sec	MAX AXIAL BEARING LOAD lb	MAX AXIAL BEARING LOAD N	MAX RADIAL BEARING LOAD lb	MAX RADIAL BEARING LOAD N	DISTANCE BETWEEN SHAFT BEARINGS in	DISTANCE BETWEEN SHAFT BEARINGS mm
1(000)	2.3	1.0	.0022	.0010	1.000	25.4	.007	.115	.39	.64	180°	120	534	300	1334	1.375	34.9
2(000)	3.3	1.5	.0043	.0020	1.000	25.4	.014	.229	.78	1.28	180°						
3(000)	6.9	3.1	.0064	.0029	1.375	34.9	.019	.312	1.11	1.21	180°	240	1068	600	2669	2.188	55.6
4(000)	9.7	4.4	.0127	.0058	1.375	34.9	.038	.623	2.22	3.64	180°						
5(000)	10.7	4.8	.0093	.0042	2.000	50.8	.041	.672	2.36	3.87	180°	370	1646	925	4114	2.235	56.8
6(000)	15.7	7.1	.0185	.0084	2.000	50.8	.082	1.344	4.72	7.74	180°						
7(000)	34.4	15.6	.0289	.0131	3.000	76.2	.185	3.032	10.60	17.37	180°	800	3558	2000	8896	3.750	95.3
8(000)	42.2	19.1	.0578	.0262	3.000	76.2	.370	6.064	21.20	34.75	180°						

HYD SERIES	OPTION psi [bar] PLAIN		-P		-D		-E OR -M	
1000	—	—	—	—	—	—	—	—
2000	1000	[69]	750	[52]	750	[52]	—	—
3000	—	—	—	—	—	—	—	—
4000	—	—	750	[52]	750	[52]	—	—
5000	—	—	—	—	—	—	750	[52]
6000	—	—	750	[52]	750	[52]	750	[52]
7000	—	—	—	—	—	—	500	[35]
8000	—	—	750	[52]	750	[52]	500	[35]

NOTE: **All hydraulic ratings are based on non-shock hydraulic service.

PRESSURE RATINGS FOR OPTIONS

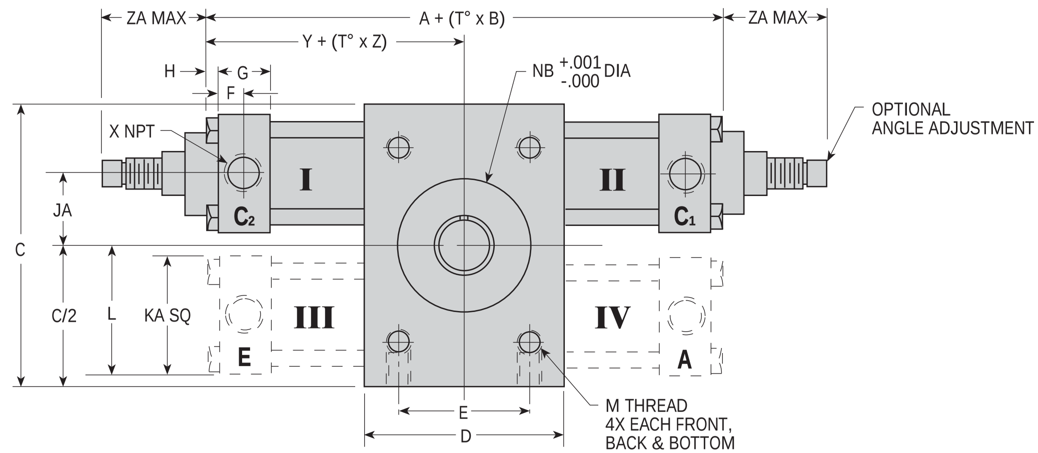
All pneumatic rotary actuators have a maximum pressure rating of 150 psi [10 bar] air. Most hydraulic rotary actuators have a maximum pressure rating of 1500 psi [100 bar], except as noted in the chart.

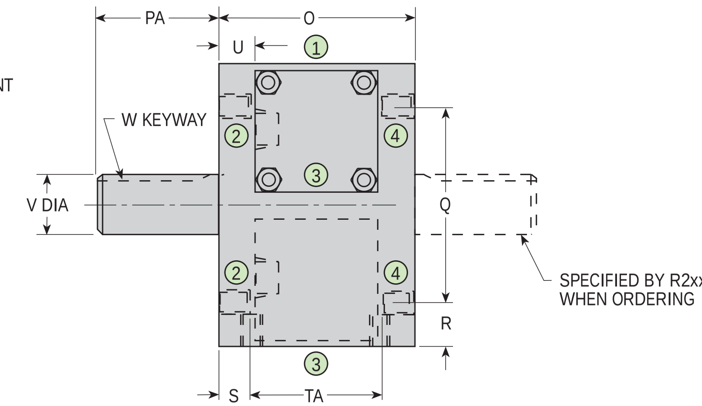
Minimum factor of safety at maximum rated hydraulic pressure for output shaft is 2:1, and for hydraulic chambers is 3:1. Consult PHD for proof pressure data. Hydraulic ratings based on non-shock, hydraulic service.

1000-8000

SIZING AND APPLICATION ASSISTANCE
See PHD Product Sizing Catalog for specific and complete sizing information.
Online sizing assistance is available at: ***www.phdinc.com/apps/sizing***

IMPERIAL





CAP STYLE	SERIES	A	B	C	D	E	F	G	H	JA	KA	L	M	NB	O	PA	Q	R	S	TA	U	V	W	X	Y	Z	ZA
		LETTER DIMENSION																									
PLAIN	1000 & 2000	5.698	.0174	3.000	2.000	1.500	.250	.500	0.00	.750	1.375	1.437	1/4-20 x .312 DP	1.125 x .056 DP	2.000	.875	2.000	.500	.250	1.500	.312	.4998/.5003	1/8 x 1/16 x .625	1/8	2.849	.0087	0.00
-A	1000 & 2000	6.198	.0174	3.000	2.000	1.500	.500	.750	0.00	.750	1.375	1.437	1/4-20 x .312 DP	1.125 x .056 DP	2.000	.875	2.000	.500	.250	1.500	.312	.4998/.5003	1/8 x 1/16 x .625	1/8	3.099	.0087	1.125
BOTH	3000 & 4000	7.906	.026	4.250	3.000	2.000	.344	.688	.250	1.156	1.875	2.094	5/16-18 x .500 DP	2.000 x .039 DP	3.000	1.875	3.000	.625	.500	2.000	.562	.8748/.8753	3/16 x 3/32 x 1.500	1/4	3.953	.013	1.500
BOTH	5000 & 6000	9.126	.026	5.000	4.000	2.500	.375	.750	.203	1.156	2.250	2.281	3/8-16 x .625 DP	2.1654 x .052 DP	3.000	1.875	3.500	.750	.500	2.000	.375	1.124/1.125	1/4 x 1/8 x 1.500	1/4	4.563	.013	1.875
BOTH	7000 & 8000	12.160	.052	8.000	5.000	3.000	.469	1.062	.437	1.875	3.500	3.625	3/4-10 x 1.250 DP	3.3465 x .120 DP	5.000	3.500	5.000	1.500	1.250	2.500	.750	1.749/1.750	3/8 x 3/16 x 3.000	3/8	6.080	.026	2.875

OPTION LOCATION REFERENCE

ACTUATOR TYPE	LETTER OPTION REFERENCED BY TUBE NUMBER											PORT & NEEDLE LOCATIONS REFERENCED BY CIRCLED NUMBERS														
	-A		-B		-D		-P					STANDARD			-O			-Q			-T			-I		
	-A1	-A2	-B1	-B2	-D1	-D2	-P1	-P2	-M	-E	-N	PORT	-P	-D	PORT	-P	-D	PORT	-P	-D	PORT	-P	-D	PORT	-P	-D
R1xA & R2xA	II	I	II	I	II	I	II	I	I & II	I & II	I & II	2	1	1	1	2	2	3	2	2	4	1	1	1, 3	4	4
R1xH & R2xH	II	I	N/A	N/A	II	I	II	I	I & II	I & II	N/A	2	1	1	1	2	2	3	2	2	4	1	1	1, 3	4	4

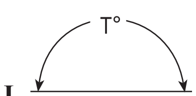
QUICK REFERENCE FOR: A + (T° x B)

SERIES	DEGREE OF ROTATION					
	45	90	180	270	360	450
*1000 & 2000	6.481	7.264	8.830	10.396	11.962	13.528
3000 & 4000	9.076	10.246	12.586	14.926	17.266	19.606
5000 & 6000	10.296	11.466	13.806	16.146	18.486	20.826
7000 & 8000	14.500	16.840	21.520	26.200	30.880	35.560

*Dimensions calculated using plain cap style. Add .250 to dimension for each -A style cap used on Series 1000/2000 only.

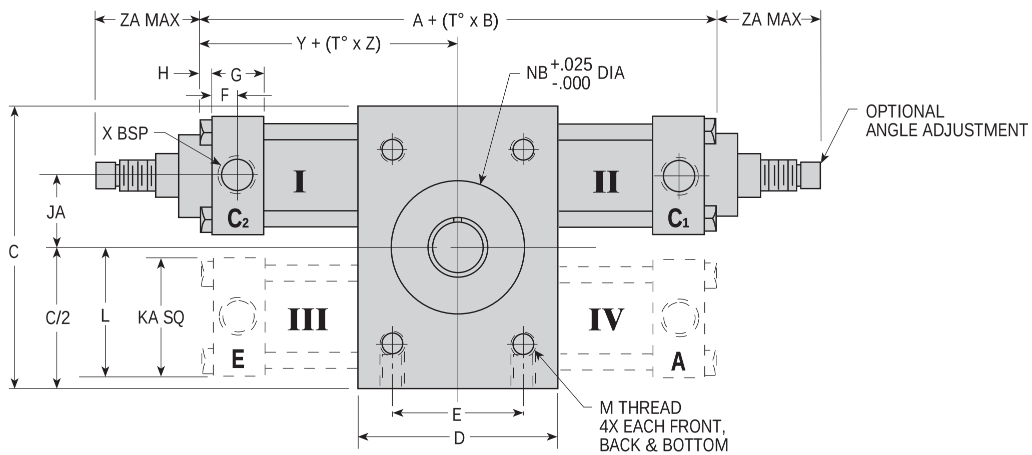
SHAFT KEYWAY: SHOWN AT MID-ROTATION
PORT POSITION: INDICATED BY CIRCLED NUMBERS
-O & -Q AVAILABLE ON SERIES 1000, 3000, 5000, & 7000 ONLY
TUBES III & IV: INCLUDED ON SERIES 2000, 4000, 6000, & 8000 UNITS ONLY
MTG. HOLES: CENTERED ON CENTERLINE OF ACTUATOR BODY
CUSHIONS: SERIES 1000 & 2000 ACTUATORS
ADD 1/2" TO RESPECTIVE "A" AND "Y" DIMENSIONS FOR EACH CUSHION

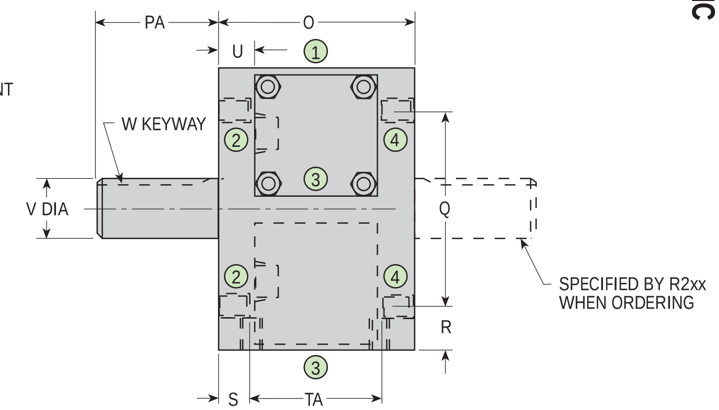
I: PORT PRESSURIZED - FULL CCW POSITION
C_1 ON SERIES 1000, 3000, 5000, & 7000
OR C_1 & E ON SERIES 2000, 4000, 6000, & 8000



II: PORT PRESSURIZED - FULL CW POSITION
C_2 ON SERIES 1000, 3000, 5000, & 7000
OR C_2 & A ON SERIES 2000, 4000, 6000, & 8000

METRIC





CAP STYLE	SERIES	A	B	C	D	E	F	G	H	JA	KA	L	M	NB	O	PA	Q	R	S	TA	U	IMPERIAL SHAFTS* V	IMPERIAL SHAFTS* W	METRIC SHAFTS* V	METRIC SHAFTS* W	X	Y	Z	ZA
PLAIN	1000 & 2000	145	0.44	76	51	38.1	6	13	0	19	35	36	M6 x 1.0 x 8	28.58 x 1.4 DP	50.8	22	50.8	13	6	38.1	8	12.69/12.71	3.15 x 1.59 x 16	12.00/11.97	4 x 2.5 x 15	1/8	72	0.22	0
-A	1000 & 2000	157	0.44	76	51	38.1	13	19	0	19	35	36	M6 x 1.0 x 8	28.58 x 1.4 DP	50.8	22	50.8	13	6	38.1	8	12.69/12.71	3.15 x 1.59 x 16	12.99/11.97	4 x 2.5 x 15	1/8	78	0.22	29
BOTH	3000 & 4000	201	0.66	108	76	50.8	9	17	6	29	48	53	M8 x 1.25 x 13	50.80 x 1.0 DP	76.2	48	76.2	16	13	50.8	14	22.22/22.23	4.75 x 2.36 x 38	22.00/21.96	6 x 3.5 x 32	1/4	100	0.33	38
BOTH	5000 & 6000	232	0.66	127	102	63.5	10	19	5	29	57	58	M10 x 1.5 x 16	55.00 x 1.3 DP	76.2	48	88.9	19	13	50.8	10	28.55/28.58	6.35 x 3.18 x 38	28.00/27.96	8 x 5 x 40	1/4	116	0.33	48
BOTH	7000 & 8000	309	1.33	203	127	76.2	12	27	11	48	89	92	M20 x 2.5 x 32	85.00 x 3.0 DP	127.0	89	127.0	38	32	63.5	19	44.42/44.45	9.53 x 2.36 x 78	44.00/43.96	12 x 5 x 56	3/8	154	0.66	73

(LETTER DIMENSION: A through ZA; IMPERIAL SHAFTS*: V, W; METRIC SHAFTS*: V, W)

OPTION LOCATION REFERENCE

ACTUATOR TYPE	LETTER OPTION REFERENCED BY TUBE NUMBER -A		-B		-D		-P					PORT & NEEDLE LOCATIONS REFERENCED BY CIRCLED NUMBERS STANDARD			-O			-Q			-T			-I		
	-A1	-A2	-B1	-B2	-D1	-D2	-P1	-P2	-M	-E	-N	PORT	-P	-D	PORT	-P	-D	PORT	-P	-D	PORT	-P	-D	PORT	-P	-D
R1xA & R2xA	II	I	II	I	II	I	II	I	I & II	I & II	I & II	2	1	1	1	2	2	3	2	2	4	1	1	1, 3	4	4
R1xH & R2xH	II	I	—	—	II	I	II	I	I & II	I & II	N/A	2	1	1	1	2	2	3	2	2	4	1	1	1, 3	4	4

* BOTH IMPERIAL AND METRIC SHAFT OPTIONS AVAILABLE ON METRIC BODY (IMPERIAL SHAFT = DESIGN 5, AND METRIC SHAFT = DESIGN 6). NUMBERS ARE FOR METRIC UNITS AND ARE IN mm.

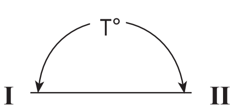
SHAFT KEYWAY: SHOWN AT MID-ROTATION
PORT POSITION: INDICATED BY CIRCLED NUMBERS
-O & -Q AVAILABLE ON SERIES 1000, 3000, 5000, & 7000 ONLY
TUBES III & IV: INCLUDED ON SERIES 2000, 4000, 6000, & 8000 UNITS ONLY
MTG. HOLES: CENTERED ON CENTERLINE OF ACTUATOR BODY
CUSHIONS: SERIES 1000 & 2000 ACTUATORS
ADD 13 mm TO RESPECTIVE "A" AND "Y" DIMENSIONS FOR EACH CUSHION

QUICK REFERENCE FOR: A + (T° x B)

SERIES	DEGREE OF ROTATION 45	90	180	270	360	450
*1000 & 2000	164.6	184.5	224.3	264.1	303.8	343.6
3000 & 4000	230.5	260.2	319.7	379.1	438.6	498.0
5000 & 6000	261.5	291.1	351.4	410.1	469.5	529.0
7000 & 8000	368.3	427.7	548.0	665.5	784.4	903.2

*Dimensions calculated using plain cap style. Add 6.3 to dimension for each -A style cap used on Series 1000/2000 only.

PORT PRESSURIZED - FULL CCW POSITION
C_1 ON SERIES 1000, 3000, 5000, & 7000
OR C_1 & E ON SERIES 2000, 4000, 6000, & 8000

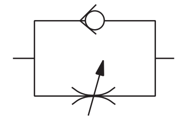


PORT PRESSURIZED - FULL CW POSITION
C_2 ON SERIES 1000, 3000, 5000, & 7000
OR C_2 & A ON SERIES 2000, 4000, 6000, & 8000

P — PORT CONTROL® BOTH DIRECTIONS

P1 — PORT CONTROL® CLOCKWISE

P2 — PORT CONTROL® COUNTERCLOCKWISE



The exclusive PHD Port Control®, "built-in" speed control valve based on the "meter-out" principle, features an adjustable needle and a separate ball check. Both are built into the rotary actuator end cap and are used to control the speed of the actuator over its entire rotation.

The self-locking needle has micrometer threads and is adjustable under pressure. It determines the orifice size which controls the exhaust volume only of the actuator proper. The separate ball check is closed while fluid is exhausting from the actuator, but opens to permit full flow of incoming fluids. The PHD Port Control® provides the optimum in speed control for rotary actuators. It saves space and eliminates the cost of fittings and installation for external flow control valves.

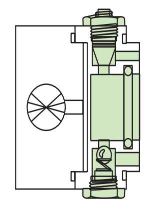
D — ADJUSTABLE CUSHIONS BOTH DIRECTIONS

D1 — ADJUSTABLE CUSHIONS CLOCKWISE

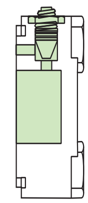
D2 — ADJUSTABLE CUSHIONS COUNTERCLOCKWISE

PHD Cushions are designed for smooth deceleration at the end of rotation. When the cushion is activated, the remaining volume in the cylinder must exhaust past an adjustable needle which controls the amount of deceleration. Effective cushion length is approximately 30° of rotation.

Cushions on Series 2000, 4000, 6000, and 8000 are furnished on one of two racks only.



1/2000
Cushion Block Style



3/8000
Poppet Style

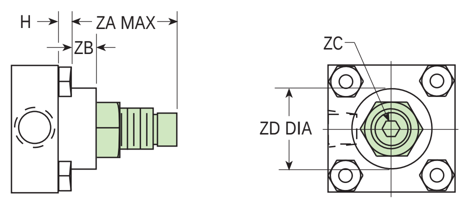
A — ANGLE ADJUSTMENT BOTH DIRECTIONS

A1 — ANGLE ADJUSTMENT CLOCKWISE

A2 — ANGLE ADJUSTMENT COUNTERCLOCKWISE

Adjusting screw(s) for reducing angle of rotation in either or both directions for use where exact degree of desired rotation cannot be predetermined or where requirements may vary during operation. Standard adjusting screw will reduce angle of rotation up to 30°. Available in conjunction with all other optional features.

Cushions are normally engaged over the last 30° of angle. The use of angle adjusting screws to reduce angle of rotation has a direct effect on the length of cushion engagement. Example: 10° angle reduction will reduce cushion engagement by 10°.



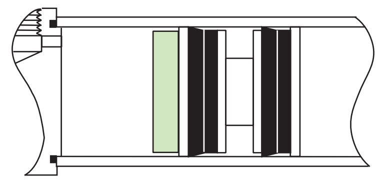
SERIES	LETTER DIMENSION				
	H	ZA	ZB	ZC	ZD
1000 & 2000	0.00 [0]	1.125 [29]	.312 [8]	3/16 HEX —	.875 [22]
3000 & 4000	.250 [6]	1.500 [38]	.375 [10]	1/4 HEX —	1.250 [32]
5000 & 6000	.203 [5]	1.875 [48]	.750 [19]	1/4 HEX —	1.250 [32]
7000 & 8000	.437 [11]	2.875 [73]	.937 [24]	3/4 FLAT [19 mm]	1.750 [45]

NUMBERS IN [ ] ARE FOR METRIC UNITS AND ARE IN mm.

B SHOCK PADS BOTH DIRECTIONS

B1 SHOCK PADS CLOCKWISE

B2 SHOCK PADS COUNTERCLOCKWISE

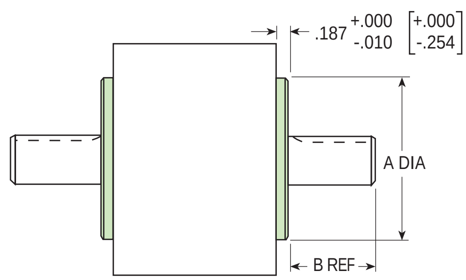


Polyurethane pads for absorption of shock and noise are available on each end of Series 1000-8000 Rotary Actuators. Reducing shock permits higher piston velocities for shorter cycle times. Reducing noise levels provides improved environment for increased productivity. Pads eliminate metal-to-metal contact between piston and end caps. **NOTE:** Air application only.

G SHAFT SEAL COVERS

Not available on Rx6x models

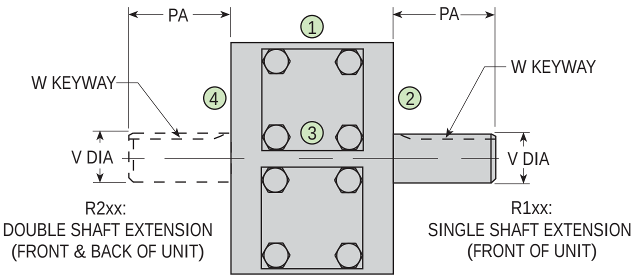
Fits all PHD Series 1000-8000, except when ordering hollow shafts. Isolates internal or external pressures. Maximum pressure differential is 500 psi [34.4 bar]. Furnished installed on actuator only (both sides). Covers are made of hard anodized aluminum. Not to be used as a pilot.



SERIES	LETTER A	LETTER B
2000	1.875 [47.63]	.688 [17.5]
4000	3.000 [76.20]	1.688 [42.9]
6000	3.250 [82.55]	1.688 [42.9]
8000	4.480 [113.79]	3.312 [84.1]

NUMBERS IN [ ] ARE FOR METRIC UNITS AND ARE IN mm.

BASIC SHAFT DIMENSIONS: R1xx and R2xx



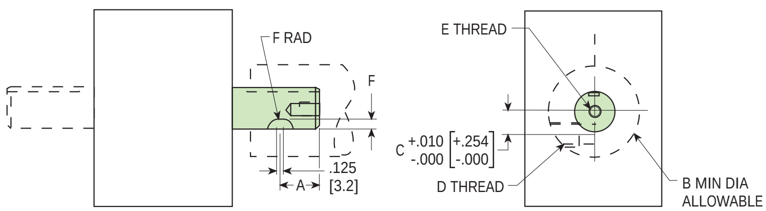
SERIES	LETTER DIMENSION				
		IMPERIAL*		METRIC**	
	PA	V	W	V	W
1000 & 2000	.875 [22]	.4998/.5003 [12.69/12.71]	1/8 x 1/16 x .625 [3.18 x 1.56 x 16]	— [12.00/11.97]	— [4 x 2.5 x 15]
3000 & 4000	1.875 [48]	.8748/.8753 [22.22/22.23]	3/16 x 3/32 x 1.500 [4.75 x 2.36 x 38]	— [22.00/21.96]	— [6 x 3.5 x 32]
5000 & 6000	1.875 [48]	1.124/1.125 [28.55/28.58]	1/4 x 1/8 x 1.500 [6.35 x 3.18 x 38]	— [28.00/27.96]	— [8 x 5 x 40]
7000 & 8000	3.500 [89]	1.749/1.750 [44.42/44.45]	3/8 x 3/16 x 3.000 [9.53 x 2.36 x 76]	— [44.00/43.96]	— [12 x 5 x 56]

NOTES:
1) **SHAFT KEYWAY:** SHOWN AT MID-ROTATION
2) *IMPERIAL SHAFT UNITS (Rx1x, Rx5x)
3) **METRIC SHAFT UNITS (Rx6x)

K PRELOADED KEYWAY SHAFT

Not available on Rx6x

Required when use with hub adaptor is desired.

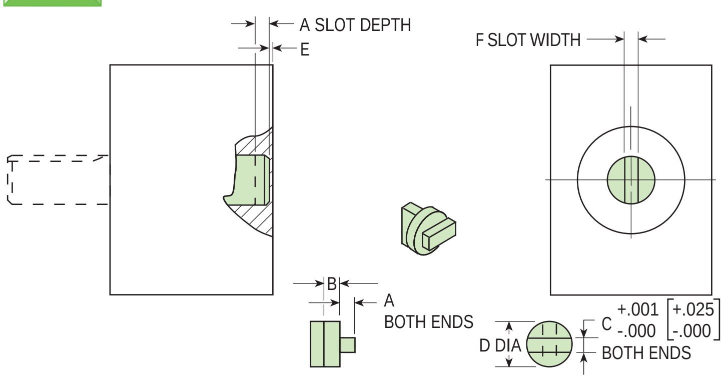


SHAFT KEYWAY: SHOWN AT MID-ROTATION
R2xx UNITS: WHEN ORDERING SPECIFY -K-K FOR PRELOAD ON BOTH SHAFT EXTENSIONS. PRELOAD WILL BE ON OPPOSITE SIDES OF SHAFT.
SET SCREW: INCLUDED WITH UNIT

SERIES	LETTER DIMENSION					
	A	B	C	D	E	F
1000 & 2000	.375 [9.5]	1.500 [38.1]	.250 [6.35]	3/8-24 [M10]	10-32 x .312 DP [M5 x 8]	.156 [4]
3000 & 4000	.812 [20.6]	2.000 [50.8]	.437 [11.11]	1/2-20 [M12]	5/16-24 x .440 DP [M8 x 11]	.220 [6]
5000 & 6000	.812 [20.6]	3.000 [76.2]	.563 [14.28]	5/8-11 [M16]	3/8-24 x .560 DP [M10 x 14]	.251 [6]
7000 & 8000	1.500 [38.1]	4.000 [101.6]	.875 [22.22]	1-8 [M24]	1/2-20 x .687 DP [M12 x 17.5]	.438 [11]

C CROSS KEY SHAFT

Not available on Rx6x

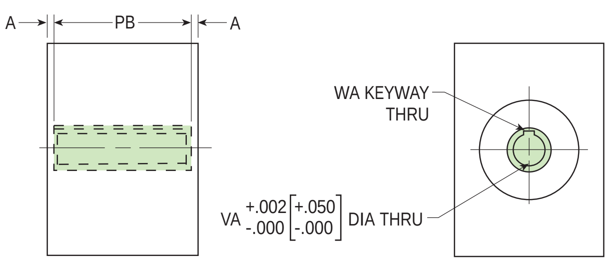


SERIES	LETTER DIMENSION					
	A	B	C	D	E	F
1000 & 2000	.250 [6.4]	.215 [5.5]	.230 [5.8]	.500 [12.7]	.118 [3]	.250 [6.3]
3000 & 4000	.250 [6.4]	.265 [6.7]	.248 [6.3]	.875 [22.2]	.120 [3]	.248 [6.3]
5000 & 6000	.437 [11]	.485 [12.3]	.500 [12.7]	1.125 [28.6]	.150 [3.8]	.5002 [12.7]
7000 & 8000	.437 [11]	.805 [20.4]	.875 [22.2]	1.750 [44.5]	.245 [6.2]	.8752 [22.2]

SHAFT KEYWAY: SHOWN AT MID-ROTATION
R2xx UNITS: WHEN ORDERING SPECIFY -C-C FOR CROSSKEY ON BOTH SHAFT EXTENSIONS
CROSSKEY: INCLUDED WITH UNIT

H HOLLOW SHAFT

Not available on Rx6x



SERIES	LETTER DIMENSION			
	A	PB	VA	WA
1000 & 2000	.042 [1.1]	1.920 [48.76]	.250 [6.35]	— —
3000 & 4000	.042 [1.1]	2.917 [74.09]	.500 [12.7]	1/8 x 1/16 [3.18 x 1.58]
5000 & 6000	.135 [3.4]	2.730 [69.34]	.687 [17.46]	3/16 x 3/32 [4.76 x 2.38]
7000 & 8000	.240 [6.1]	4.520 [114.80]	1.125 [28.57]	1/4 x 1/8 [6.35 x 3.18]

SHAFT KEYWAY: SHOWN AT MID-ROTATION

All dimensions are reference only unless specifically toleranced.

MAGNETIC PISTON FOR USE WITH PHD PROXIMITY SWITCHES

See engineering data page for Hydraulic Pressure Ratings with these options. See ordering data for magnetic piston ordering information. Switches and brackets must be ordered separately. See Switches and Sensors section for complete switch information.

E SOLID STATE SWITCHES

Series 1000-8000 Rotary Actuators may be equipped with a magnetic band (specify -E) on the pistons which activates externally mounted Solid State Switches. These switches allow the interfacing of the PHD Actuators to various logic systems. This option is for use with the following switches.

SERIES 1750 SOLID STATE SWITCHES

PART NO.	COLOR	DESCRIPTION
17503-2-06	Yellow	NPN (Sink) Type 4.5-24 VDC, 6 foot cable
17504-2-06	Red	PNP (Source) Type 4.5-24 VDC, 6 foot cable
17523-2	Yellow	NPN (Sink) Type 4.5-24 VDC, Quick Connect
17524-2	Red	PNP (Source) Type 4.5-24 VDC, Quick Connect

SWITCH BRACKETS

SERIES	PART NO. SERIES 1750 SWITCH
1000 & 2000	17000-32-5
3000 & 4000	17000-34-5
5000 & 6000	17000-38-0
7000 & 8000	17000-39-0

M REED SWITCHES

The PHD Magnetic Reed Switches may be used in situations where the Solid State Switches are not applicable. As with the Solid State Switches, a magnetic band (specify -M) on the pistons activates the externally mounted PHD Reed Switches. The Reed Switches may be used to signal a programmable controller, sequencer, relay, or in some cases, a valve solenoid. This option is for use with the following switches.

SERIES 1750 REED SWITCHES

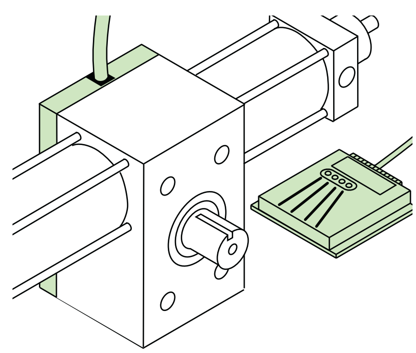
PART NO.	DESCRIPTION	
17502-2-06	White	NPN (Sink) or PNP (Source) 4.5-24 VDC, 6 foot cable
17509-3-06	Green	AC Type 110-120 VAC with Current Limit, 6 foot cable
17522-2	White	NPN (Sink) or PNP (Source) 4.5-24 VDC, Quick Connect
17529-3	Green	AC Type 110-120 VAC, Quick Connect with Current Limit

J SENSOR/SET POINT MODULE

Not available on Rx6x

PHD offers a solid state sensor transducer along with a Set Point Module which provides up to four adjustable sensing positions throughout the 180° maximum sensing range. These signals can be used as inputs to a programmable controller to signal ends of rotation in addition to multiple signals during rotation for indication of arc traveled.

The Set Point Module allows independent adjustment of each sensing position and is available for 4.5 to 24 VDC current sinking or current sourcing.



SET POINT MODULE

PART NO.	DESCRIPTION
9800-01-0300	NPN (Sink) 4.5-24 VDC
9800-01-0400	PNP (Source) 4.5-24 VDC

See Switches and Sensors section for information.

L — COUNTERCLOCKWISE UNIDIRECTIONAL CLUTCH

Not available on Rx6x or 7/8000 units
Output hub will only rotate in counterclockwise direction at specific rotation ordered.

R — CLOCKWISE UNIDIRECTIONAL CLUTCH

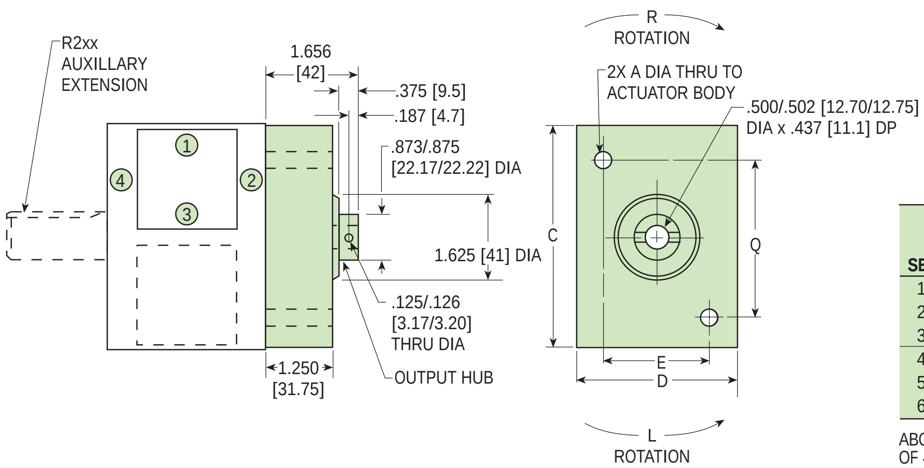
Not available on Rx6x or 7/8000 units
Output hub will only rotate in clockwise direction at specific rotation ordered.

Overrun clutch for intermittent unidirectional shaft output, available for Series 1000 through 6000.

Output hub rotates in one direction only. It remains motionless while rack and pinion reverse. Clutch repeats within ±1/2°.

Assembly features a Torrington roller clutch. Spring loaded brake shoes limit output shaft free wheeling, but are not intended for stopping external loads.

CAUTION: Any angular error will accumulate; therefore, shot pins or similar locators are necessary on index applications. Maintain shot pin location during reversal of Rotary Actuator to guarantee that clutch shaft does not move due to external forces or slight internal friction in clutch.



SERIES	LETTER DIMENSION A	C	D	E	Q
1000 & 2000	.281 [7.2]	2.938 [74.6]	2.000 [51]	1.500 [38]	2.000 [50.8]
3000 & 4000	.344 [8.7]	4.188 [106.3]	3.000 [76]	2.000 [50.8]	3.000 [76.2]
5000 & 6000	.406 [10.3]	4.938 [125.4]	4.000 [102]	2.500 [63.5]	3.500 [88.9]

SERIES	LIMITING FACTORS: MAX. INLET PRESSURE(psi)[bar]	MAX. RADIAL OR AXIAL LOAD (lb) [N]
1000	1052 [72]	5 [22]
2000	526 [36]	5 [22]
3000	372 [25]	10 [44]
4000	186 [13]	10 [44]
5000	174 [12]	15 [66]
6000	87 [6]	15 [66]

ABOVE INLET PRESSURES PROVIDE A MAXIMUM TORQUE OF 414 in-lb [46.8 Nm] ALLOWED BY THE CLUTCH

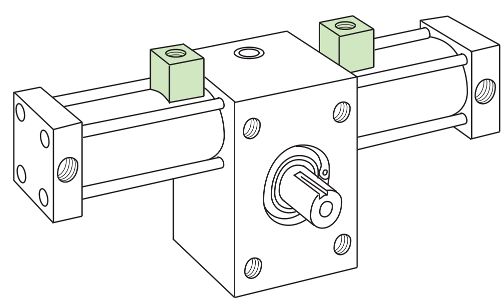
N — PILOT VALVE ACTUATOR

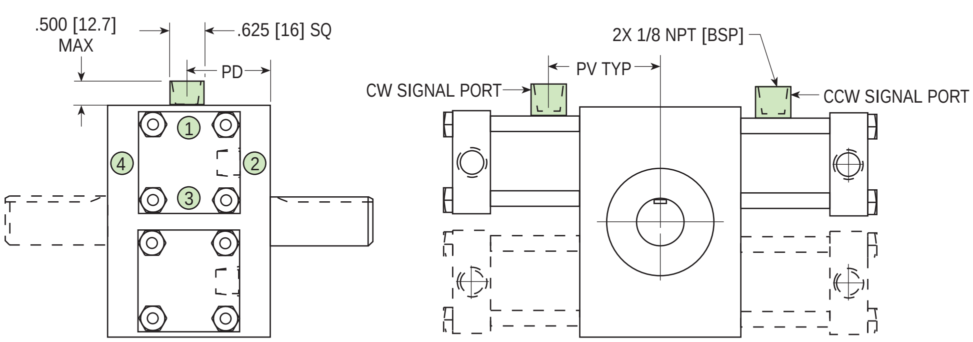
Not available on Rx6x

The PVA functions as a built-in pneumatic limit switch. An air pressure signal is provided at the end-of-piston travel as the piston seal uncovers an orifice in the block. Upon reversal of piston travel, the pilot pressure is shut off and the pilot line is vented through the rotary actuator housing.

Air pilot signal is provided approximately .03 inch [1 mm] prior to end of piston travel (or 10 to 15 degrees prior to end of rotation). For pneumatic use only.

PVA ports are located in position 1 unless otherwise specified. Not available in conjunction with angle adjustment -A option.





SERIES	LETTER DIMENSION PD	PV STANDARD	PV W/-B
1000 & 2000	1.000 [25.4]	2.191 [55.7]	1.848 [46.9]
3000 & 4000	1.500 [38.1]	2.847 [72.3]	2.410 [61.2]
5000 & 6000	1.500 [38.1]	3.436 [87.3]	2.978 [75.6]
7000 & 8000	2.500 [63.5]	4.409 [112]	3.770 [95.8]

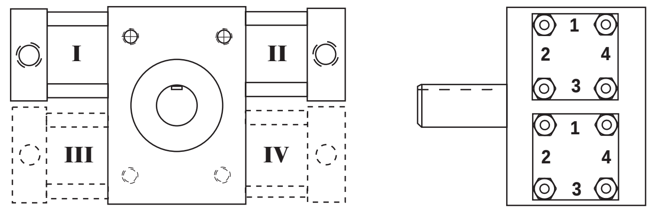
PVA UNITS WILL REQUIRE A MINIMUM ROTATION OF 45°

All dimensions are reference only unless specifically toleranced.

PORT & PORT CONTROL® LOCATIONS

Standard port location on all Series 1000-8000 Actuators is position 2. Standard PVA (-N) Locations are tubes I and II in position 1. Standard Port Control® and cushion adjustment needles are located in end caps I and II in position 1. Other port and adjusting needle locations are available as specified.

Needles may not be located in same position as ports.



I — PORT POSITION 1 TOP RACK PORT POSITION 3 BOTTOM RACK

This option positions the ports in position 1 on tubes I and II and in position 3 on tubes III and IV. This allows access to the ports on the "Top" and "Bottom" sides of the actuator.

O — PORTS POSITION 1 (N/A on 2, 4, 6, and 8000 units)

This option positions the ports in position 1.

Q — PORTS POSITION 3 (N/A on 2, 4, 6, and 8000 units)

This option positions the ports in position 3 on tubes I and II.

T — PORTS POSITION 4

This option positions the ports in position 4. This allows access to ports from the back.

V — FLUORO-ELASTOMER SEALS

Fluoro-Elastomer seals are available to achieve seal compatibility with certain fluids. Seal compatibility should be checked with the fluid manufacturer for proper application.

W — CLOSE TOLERANCE ROTATION

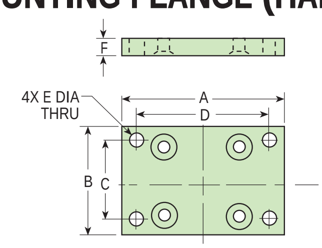
This option may be specified when a precise rotation is required and angle adjustment (see page 5-62) is not acceptable. By specifying this option, rotation will be within a tolerance of +30, -0 minutes. Standard tolerance is -0°, +10° of rotation.

Z1 — ELECTROLESS NICKEL PLATING

Electroless nickel plating is done on all externally exposed ferrous parts except the pinion shaft. This optional plating treatment gives an alternative method of protecting the unit from severe environments.

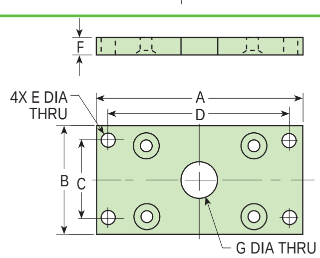
NOTE: Standard plating is Zinc and Black Oxide.

MOUNTING FLANGE (HARDWARE INCLUDED)



BOTTOM MOUNTING FLANGE

	KIT NO.		LETTER DIMENSION					
SERIES	IMPERIAL	METRIC	A	B	C	D	E	F
1000 & 2000	13756	14320	4.250 [108]	2.000 [51]	1.625 [41.3]	2.625 [66.7]	.281 [7.1]	.250 [6.3]
3000 & 4000	13757	14321	4.500 [114]	3.000 [76]	2.375 [60.3]	3.875 [98.4]	.406 [10.3]	.437 [11.1]
5000 & 6000	13758	14322	4.500 [114]	4.000 [102]	3.375 [85.7]	3.875 [98.4]	.406 [10.3]	.437 [11.1]



SIDE MOUNTING FLANGE

	KIT NO.		LETTER DIMENSION						
SERIES	IMPERIAL	METRIC	A	B	C	D	E	F	G
1000 & 2000	13759	14316	4.250 [108]	2.000 [51]	1.375 [34.9]	3.625 [92.1]	.281 [7.1]	.250 [6.3]	.625 [15.9]
3000 & 4000	13760	14317	5.750 [146]	3.000 [76]	2.125 [54.0]	5.125 [130.2]	.406 [10.3]	.437 [11.1]	1.000 [25.4]
5000 & 6000	13761	14318	6.500 [165]	4.000 [102]	3.375 [85.7]	5.875 [149.2]	.406 [10.3]	.437 [11.1]	1.250 [31.8]
7000 & 8000	13762	14319	12.000 [305]	5.000 [127]	3.000 [76.2]	10.000 [254.0]	.781 [19.8]	.750 [19.1]	1.875 [47.6]

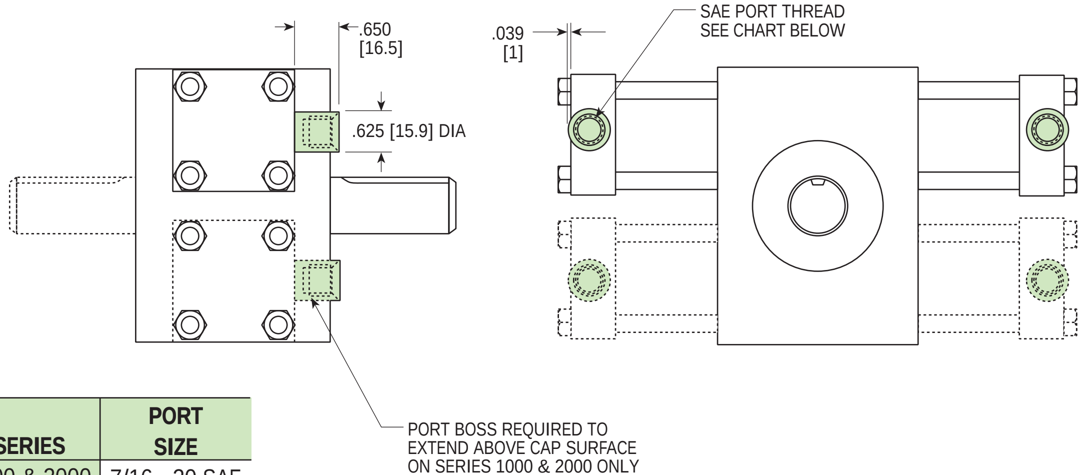
S

SAE PORTS FOR HYDRAULIC FLUID

Not available on Rx6x or RxxA

SAE Ports are available on most PHD hydraulic Rotary Actuators. The Series 1000 and 2000 Rotary Actuators require a boss which is brazed to the caps.

Dimensions for this boss are shown below. Consult PHD for optional port position or units with Port Controls.

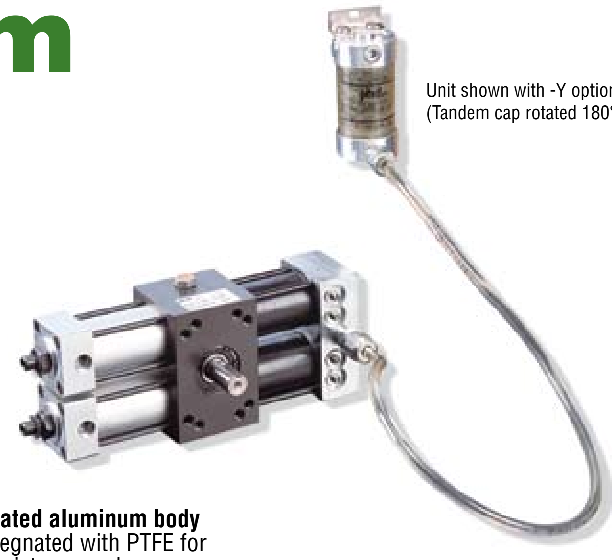


SERIES	PORT SIZE
1000 & 2000	7/16 - 20 SAE
3000 & 4000	7/16 - 20 SAE
5000 & 6000	9/16 - 18 SAE
7000 & 8000	3/4 - 16 SAE

All dimensions are reference only unless specifically toleranced.

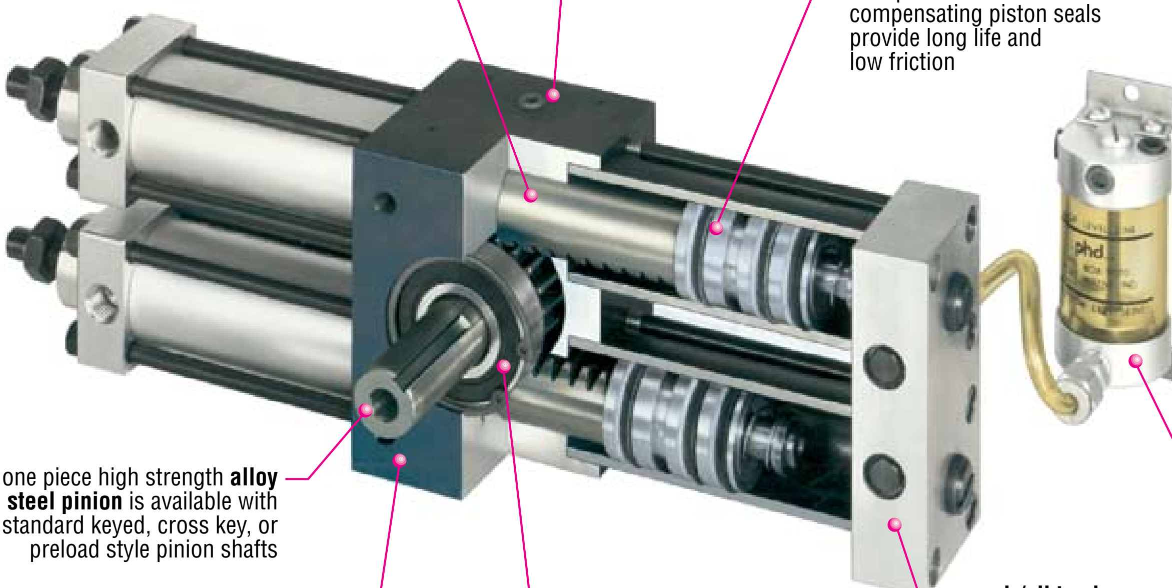
2000-8000 air/oil tandem

SMOOTH ROTATION AND CONTROLLED VELOCITY



Unit shown with -Y option
(Tandem cap rotated 180°)

OUTPUT TORQUES TO 1,590 in-lb [179 Nm]



Major Benefits

- Smooth rotation throughout rotation
- Controlled velocity

Industry Uses

- Automotive
- General industrial machines

UNITS WITH IMPERIAL SHAFTS AND KEYWAY

TO ORDER SPECIFY:
Type, Design No., Series,
Angle of Rotation, and Options.

DESIGN NO.
3 - Imperial - Ports and mounting holes are imperial
8 - Metric - Ports and mounting holes are metric. Pinion shaft and keyways are imperial.
9 - Metric Complete

SERIES
2 (000) 1" Bore Double Rack
4 (000) 1-3/8" Bore Double Rack
6 (000) 2" Bore Double Rack
8 (000) 3" Bore Double Rack (Oil Section is 2" Bore)

CUSHION
D - Cushions both directions
D1 - Cushion clockwise
D2 - Cushion counterclockwise

ANGLE ADJUSTMENT
A - Angle adjustment both ends
A1 - Angle adjustment clockwise 30°
A2 - Angle adjustment counterclockwise 30°

3 R1 3 R 2 180 - 90 - D - A - M-V

3 ROTARY POSITIONS
Use this digit for 3 Position Tandems only.

TYPE
R1 - Single Shaft
R2 - Double Shaft

FLUID MEDIA
R - Air/Oil Tandem

ANGLE OF ROTATION STANDARD ANGLES
45°, 90°, 180°, 270°, 360°, and 450°
For other available rotations, consult PHD.

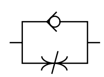
ANGLE OF ROTATION FROM POSITION I TO POSITION II
Use this digit for 3 Position Tandems only.

OPTIONS
E - Magnetic Piston for Solid State Switch
I - Port Position 1 top rack
Port Position 3 bottom rack
M - Magnetic Piston for Reed Switch
T - Port in Position 4
V - Fluoro-Elastomer Seals
W - Close Tolerance Rotation, +30 minutes, -0 (Not available on 3 positions 3RxxR units.)
Y - Tandem Cap rotated 180°
Z1 - Electroless Nickel Plate

DESIGN NO. 3 AND 8 OPTIONS ONLY
C - Cross Key Pinion Shaft
G - Shaft Seal both sides
H - Hollow Pinion Shaft (not available on type R2xR)
J - Hall Sensor for rotations not exceeding 180° (Set Point Module is ordered separately)
K - Preload Keyway Pinion Shaft (Required for use with hub adaptors)
L - Counterclockwise Unidirectional Clutch (Not available on 8000 units)
N - Pilot Valve Actuator (PVA)
R - Clockwise Unidirectional Clutch (Not available on 8000 units)

NOTE: Sensor must be used with a PHD Set Point Module. See Switches and Sensors section for information and ordering data.

PORT CONTROL©



BUILT-IN METER OUT FLOW CONTROL VALVE
Port Control is standard on all Air/Oil Tandem Actuators.

PROXIMITY SWITCH MOUNTING BRACKETS

SERIES	SIZE NO.
2000	-32
4000	-34
6000	-38
8000	-39

See Switches and Sensors section for complete ordering information.

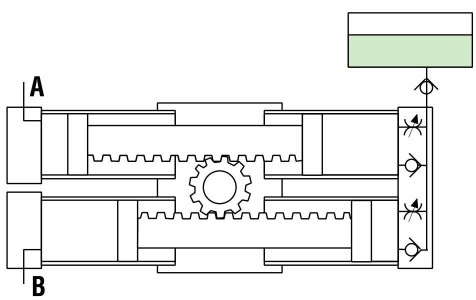
⚠ **Options may affect unit length. See unit dimension and options pages for adders.**

UNIQUE ROTARY ACTUATORS ARE AVAILABLE. SEE UNIQUE PRODUCTS AT THE END OF THIS SECTION.

SPECIFICATIONS	TANDEM SERIES 2000-8000
PNEUMATIC OPERATING PRESSURE	20 to 150 psi [1.4 to 10 bar]
OPERATING TEMPERATURE	-20° to 180°F [-29° to 82°C]
FULL (TOTAL) ROTATIONAL TOLERANCE	Nominal rotation +10°/-0°
MID-ROTATIONAL TOLERANCES (3-POSITION UNIT)	(see chart below for mid-position tolerance)
BACKLASH AT ANY MID-ROTATION POINT AND AT END OF ROTATION WITHOUT -A OPTION	1° (2000), 0° 30' (4000, 6000) 0° 15' (8000)
AT END OF ROTATION WITH -A OPTION* (DOUBLE RACK)	0° (2000, 4000, 6000, 8000)
AT MID-POSITION LOCATION (3 POSITION UNIT)	(see chart below for mid-position backlash)
LUBRICATION	Factory lubricated for rated life
MAINTENANCE	Field repairable

NOTE: *Angle adjustment screw must be engaged or adjusted to achieve 0° backlash. (-A standard on 3-position units)

SIZE	WEIGHT BASE lb	WEIGHT BASE kg	WEIGHT ADDER lb/°	WEIGHT ADDER kg/°	BORE DIAMETER in	BORE DIAMETER mm	DISPLACEMENT VOLUME/DEG in^3/°	DISPLACEMENT VOLUME/DEG cm^3/°	THEORETICAL TORQUE OUTPUT in-lb/psi	THEORETICAL TORQUE OUTPUT Nm/bar	MAX SPEED AT 80 psi deg/sec	MAX AXIAL BEARING LOAD lb	MAX AXIAL BEARING LOAD N	MAX RADIAL BEARING LOAD lb	MAX RADIAL BEARING LOAD N	DISTANCE BETWEEN SHAFT BEARINGS in	DISTANCE BETWEEN SHAFT BEARINGS mm
2(000)	4.5	2.0	.0059	.0027	1.000	25.4	.007	.115	.39	.64	366°	120	534	300	1334	1.375	34.9
4(000)	11.5	5.2	.0161	.0073	1.375	34.9	.019	.312	1.11	1.82	348°	240	1068	600	2669	2.188	55.6
6(000)	18.1	8.2	.0244	.0111	2.000	50.8	.041	.672	2.36	3.87	216°	370	1646	925	4114	2.235	56.8
8(000)	41.0	18.6	.0581	.0264	3.000	76.2	.185	3.032	10.60	17.37	156°	800	3558	2000	8896	3.750	95.3



3-POSITION MID-POSITION TOLERANCES & BACKLASH

SERIES	TOLERANCE	BACKLASH
2000	±1°	±1° 30'
4000 & 6000	±0° 30'	±1° 15'
8000	±0° 15'	1°

OPERATING PRINCIPLE

This feature is available on Series 2000, 4000, 6000, and 8000. One end functions as a control member only, reducing the effective output torque to match 1000, 3000, 5000, and 7000 respectively.

The illustration shows a tandem actuator with built-in Port Controls®, crossover manifold and oil reservoir. The latter serves as an accumulator to compensate for oil volume changes due to temperature variation.

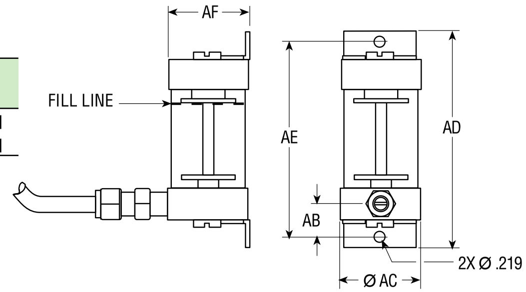
NOTE: The reservoir should have 20 psi [1.4 bar] pressure at all times to ensure the system remains purged.

SIZING AND APPLICATION ASSISTANCE
See PHD Product Sizing Catalog for specific and complete sizing information. Online sizing assistance is available at:
www.phdinc.com/apps/sizing

IMPERIAL

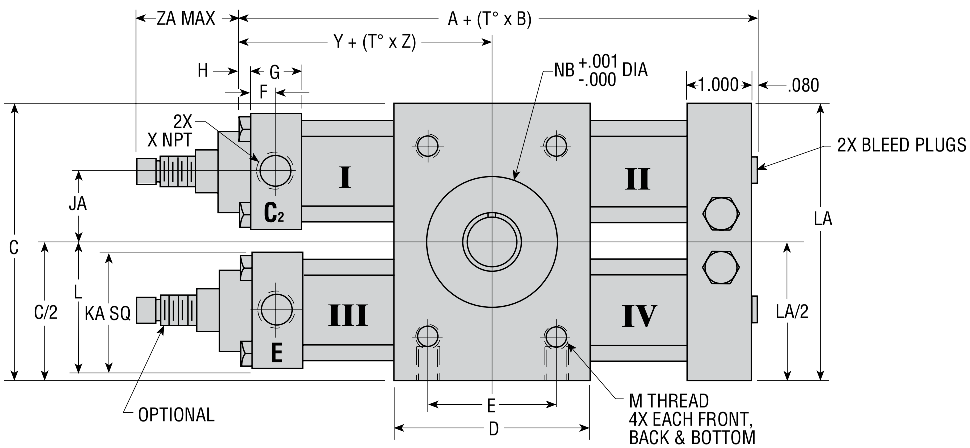
TANK DIMENSIONS

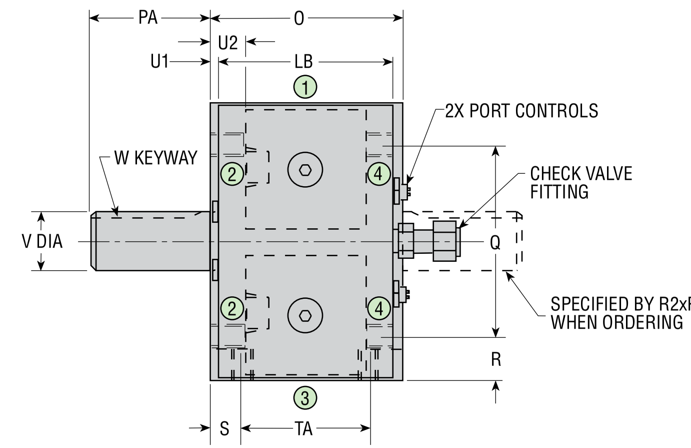
RESERVOIR PART NO.	AB	AC	AD	AE	AF
13459-02-2	.647	2.500	5.500	5.125	2.531
13459-03-2	.545	1.500	3.875	3.500	1.531



RESERVOIR ASSEMBLY IS INCLUDED WITH UNIT.
SERIES 2000, 4000, & 6000 UNITS USE PART NO. 13459-03-2.
SERIES 8000 UNITS USE PART NO. 13459-02-2.

NOTE: THE RESERVOIR SHOULD HAVE 20 PSI PRESSURE AT ALL TIMES TO ENSURE THE SYSTEM REMAINS PURGED.





CAP STYLE	SERIES	A	B	C	D	E	F	G	H	JA	KA	L	LA	LB	M	NB	O	PA	Q	R	S	TA	U1	U2	V	W	X	Y	Z	ZA
		LETTER DIMENSION																												
PLAIN	2000	6.215	.0174	3.000	2.000	1.500	.250	.500	0.00	.750	1.375	1.437	2.875	1.750	1/4-20 x .312 DP	1.125 x .056 DP	2.000	.875	2.000	.500	.250	1.500	.125	.312	.4998/.5003	1/8 x 1/16 x .625	1/8	2.849	.0087	0
-A	2000	6.465	.0174	3.000	2.000	1.500	.500	.750	0.00	.750	1.375	1.437	2.875	1.750	1/4-20 x .312 DP	1.125 x .056 DP	2.000	.875	2.000	.500	.250	1.500	.125	.312	.4998/.5003	1/8 x 1/16 x .625	1/8	3.099	.0087	1.125
BOTH	4000	7.986	.026	4.250	3.000	2.000	.344	.688	.250	1.156	1.875	2.094	4.187	2.750	5/16-18 x .500 DP	2.000 x .039 DP	3.000	1.875	3.000	.625	.500	2.000	.125	.562	.8748/.8753	3/16 x 3/32 x 1.500	1/4	3.953	.013	1.500
BOTH	6000	9.190	.026	5.000	4.000	2.500	.375	.750	.203	1.156	2.250	2.281	4.687	2.750	3/8-16 x .625 DP	2.1654 x .052 DP	3.000	1.875	3.500	.750	.500	2.000	.125	.375	1.124/1.125	1/4 x 1/8 x 1.500	1/4	4.563	.013	1.875
BOTH	8000	11.128	.052	8.000	5.000	3.000	.469	1.062	.437	1.875	3.500	3.625	6.125	3.000	3/4-10 x 1.250 DP	3.3465 x .120 DP	5.000	3.500	5.000	1.500	1.250	2.500	1.000	.750	1.749/1.750	3/8 x 3/16 x 3.000	3/8	6.080	.026	2.875

OPTION LOCATION REFERENCE

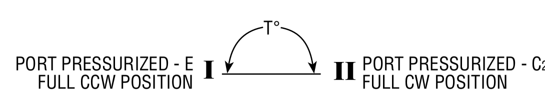
ACTUATOR TYPE	LETTER OPTION REFERENCED BY TUBE NUMBER								PORT & NEEDLE LOCATIONS REFERENCED BY CIRCLED NUMBERS								
	-A		-D		-P				STANDARD			-T			-I		
	-A1	-A2	-D1	-D2	-P1	-P2	-M	-E	PORT	-P	-D	PORT	-P	-D	PORT	-P	-D
R1xR & R2xR	III	I	II	IV	STANDARD		I & III	I & III	2	4	4	4	4	4	1 & 3	4	4

QUICK REFERENCE FOR: A + (T° x B)

SERIES	DEGREE OF ROTATION					
	45	90	180	270	360	450
*2000	6.998	7.781	9.347	10.913	12.479	14.045
4000	9.156	10.326	12.666	15.006	17.346	19.686
6000	10.360	11.530	13.870	16.210	18.550	20.890
8000	13.468	15.808	20.488	25.168	29.848	34.528

*Dimensions calculated using plain cap style. Add .250 to dimension for each -A style cap used on Series 2000 only.

SHAFT KEYWAY: SHOWN AT MID-ROTATION
PORT POSITION: INDICATED BY CIRCLED NUMBERS
MTG. HOLES: CENTERED ON CENTERLINE OF ACTUATOR BODY



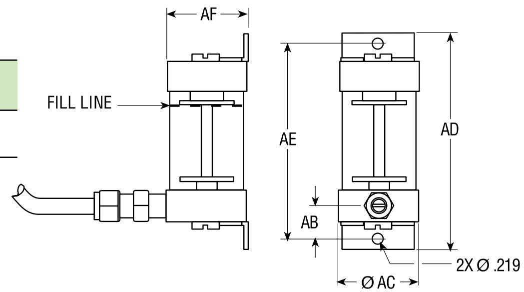
All dimensions are reference only unless specifically toleranced.

METRIC

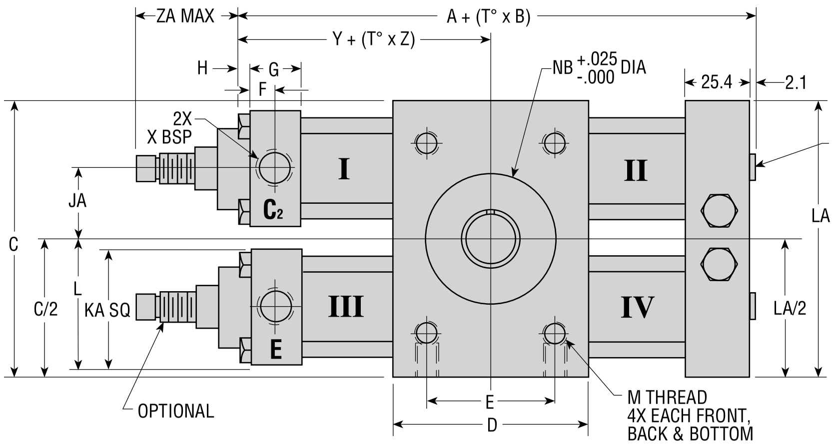
RESERVOIR ASSEMBLY IS INCLUDED WITH UNIT.
SERIES 2000, 4000, & 6000 UNITS USE PART NO. 68397-03-2.
SERIES 8000 UNITS USE PART NO. 68397-02-2.

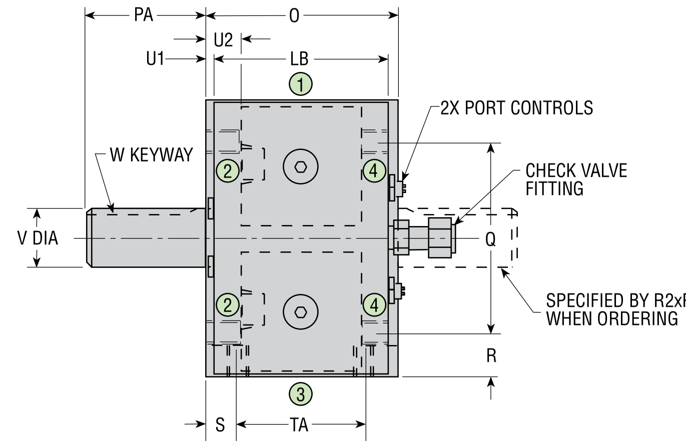
NOTE: THE RESERVOIR SHOULD HAVE 1.4 bar PRESSURE AT ALL TIMES TO ENSURE THE SYSTEM REMAINS PURGED.

TANK DIMENSIONS



RESERVOIR PART NO.	AB	AC	AD	AE	AF
13459-02-2	16.4	63.5	139.7	130.2	64.3
13459-03-2	13.8	38.1	98.4	88.9	38.9





CAP STYLE	SERIES	A	B	C	D	E	F	G	H	JA	KA	L	LA	LB	M	NB	O	PA	Q	R	S	TA	IMPERIAL SHAFTS* V	IMPERIAL SHAFTS* W	METRIC SHAFTS* V	METRIC SHAFTS* W	U1	U2	X	Y	Z	ZA
PLAIN	2000	158	0.44	76	51	38.1	6	13	0	19	35	36	73	44	M6 x 1.0 x 8	28.58 x 1.4	50.8	22	50.8	13	6	38.1	12.69/12.71	3.15 x 1.59 x 16	12.00/11.97	4 x 2.5 x 15	3	8	G1/8	72	0.22	0
-A	2000	165	0.44	76	51	38.1	13	19	0	19	35	36	73	44	M6 x 1.0 x 8	28.58 x 1.4	50.8	22	50.8	13	6	38.1	12.69/12.71	3.15 x 1.59 x 16	12.00/11.97	4 x 2.5 x 15	3	8	G1/8	78	0.22	29
BOTH	4000	203	0.66	108	76	50.8	9	17	6	29	48	53	106	70	M8 x 1.25 x 13	50.80 x 1.0	76.2	48	76.2	16	13	50.8	22.22/22.23	4.75 x 2.36 x 38	22.00/21.96	6 x 3.5 x 32	3	14	G1/4	100	0.33	38
BOTH	6000	233	0.66	127	102	63.5	10	19	5	29	57	58	119	70	M10 x 1.5 x 16	55.00 x 1.3	76.2	48	88.9	19	13	50.8	28.55/28.58	6.35 x 3.18 x 38	28.00/27.96	8 x 5 x 40	3	10	G1/4	116	0.33	48
BOTH	8000	283	1.32	203	127	76.2	12	27	11	48	89	92	156	76	M20 x 2.5 x 32	85.00 x 3.0	127.0	89	127	38	32	63.5	44.42/44.45	9.53 x 2.36 x 78	44.00/43.96	12 x 5 x 56	25	19	G3/8	154	0.66	73

* BOTH IMPERIAL AND METRIC SHAFT OPTIONS AVAILABLE ON METRIC BODY (IMPERIAL SHAFT = DESIGN 8, AND METRIC SHAFT = DESIGN 9).
NUMBERS FOR METRIC UNITS AND ARE IN mm.

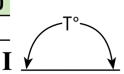
QUICK REFERENCE FOR: A + (T° x B)

SERIES	DEGREE OF ROTATION 45	90	180	270	360	450
**2000	177.7	197.6	237.4	277.2	317.0	356.7
4000	232.6	262.2	321.7	381.2	440.6	500.0
6000	263.1	292.9	352.3	411.7	471.2	530.9
8000	342.1	401.5	520.4	639.3	758.1	877.0

**Dimensions calculated using plain cap style. Add 6.3 to dimension for each -A style cap used on Series 2000 only.

OPTION LOCATION REFERENCE

ACTUATOR TYPE	LETTER OPTION REFERENCED BY TUBE NUMBER: -A -A1	-A -A2	-D -D1	-D -D2	-P -P1 -P2	-M	-E	PORT & NEEDLE LOCATIONS REFERENCED BY CIRCLED NUMBERS: STANDARD PORT	STANDARD -P	STANDARD -D	-T PORT	-T -P	-T -D	-I PORT	-I -P	-I -D
R1xR & R2xR	III	I	II	IV	STANDARD	I & III	I & III	2	4	4	4	4	4	1 & 3	4	4



PORT PRESSURIZED - E I FULL CCW POSITION

II PORT PRESSURIZED - C2 FULL CW POSITION

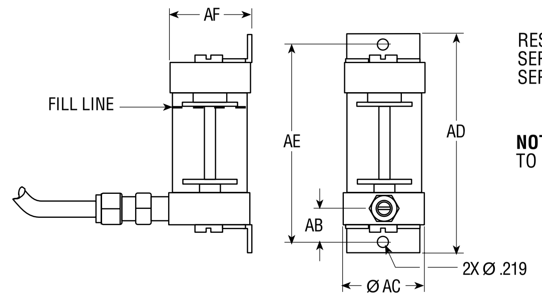
SHAFT KEYWAY: SHOWN AT MID-ROTATION
PORT POSITION: INDICATED BY CIRCLED NUMBERS
MTG. HOLES: CENTERED ON CENTERLINE OF ACTUATOR BODY

DIMENSIONS: 3-POSITION AIR/OIL TANDEM

IMPERIAL

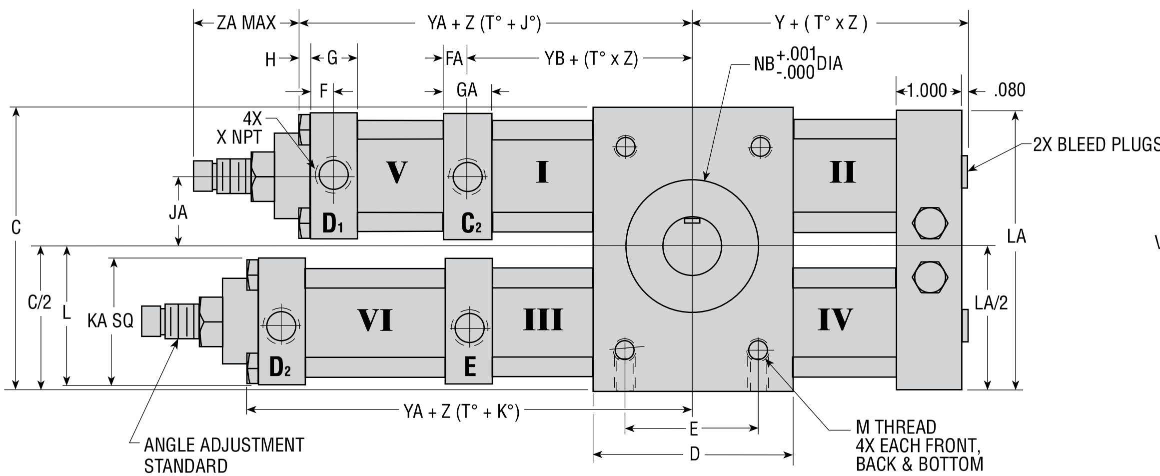
TANK DIMENSIONS

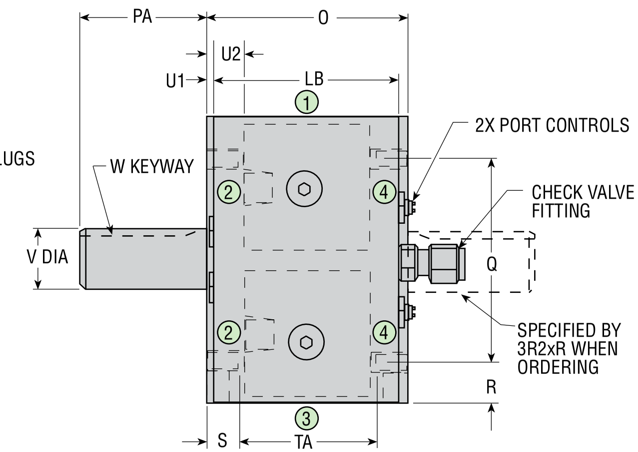
RESERVOIR PART NO.	AB	AC	AD	AE	AF
13459-02-2	.647	2.500	5.500	5.125	2.531
13459-03-2	.545	1.500	3.875	3.500	1.531



RESERVIOR ASSEMBLY IS INCLUDED WITH UNIT.
SERIES 2000, 4000, & 6000 UNITS USE PART NO. 13459-03-2.
SERIES 8000 UNITS USE PART NO. 13459-02-2.

NOTE: THE RESERVOIR SHOULD HAVE 20 PSI PRESSURE AT ALL TIMES TO ENSURE THE SYSTEM REMAINS PURGED.



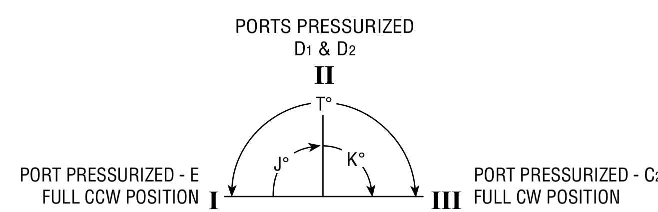


SERIES	C	D	E	F	FA	G	GA	H	JA	KA	L	LA	LB	M	NB	O	PA	Q	R	S	TA	U1	U2	V	W	X	Y	YA	YB	Z	ZA
2000	3.000	2.000	1.500	.500	.500	.750	.750	0.00	.750	1.375	1.437	2.875	1.750	1/4-20 x .312 DP	1.125 x .056 DP	2.000	.875	2.000	.500	.250	1.500	.125	.312	.4998/.5003	1/8 x 1/16 x .625	1/8	3.366	5.983	2.599	.0087	1.125
4000	4.250	3.000	2.000	.344	.375	.688	.719	.250	1.156	1.875	2.094	4.187	2.750	5/16-18 x .500 DP	2.000 x .039 DP	3.000	1.875	3.000	.625	.500	2.000	.125	.562	.8748/.8753	3/16 x 3/32 x 1.500	1/4	4.033	6.721	3.360	.013	1.500
6000	5.000	4.000	2.500	.375	.344	.750	.719	.203	1.156	2.250	2.281	4.687	2.750	3/8-16 x .625 DP	2.1654 x .052 DP	3.000	1.875	3.500	.750	.500	2.000	.125	.375	1.124/1.125	1/4 x 1/8 x 1.500	1/4	4.627	7.325	3.980	.013	1.875
8000	8.000	5.000	3.000	.469	.469	1.062	1.062	.437	1.875	3.500	3.625	6.125	3.000	3/4-10 x 1.250 DP	3.3465 x .120 DP	5.000	3.500	5.000	1.500	1.250	2.500	1.000	.750	1.749/1.750	3/8 x 3/16 x 3.000	3/8	5.048	9.865	5.236	.026	2.875

OPTION LOCATION REFERENCE

ACTUATOR TYPE	LETTER OPTION REFERENCED BY TUBE NUMBER						PORT & NEEDLE LOCATIONS REFERENCED BY CIRCLED NUMBERS								
	-A	-D		-P	-M	-E	STANDARD			-T			-I		
		-D1	-D2	-P1 -P2	I & III	I & III	PORT	-P	-D	PORT	-P	-D	PORT	-P	-D
3R1xR & 3R2xR	STANDARD	II	IV	STANDARD	V & VI	V & VI	2	4	4	4	4	4	1 & 3	4	4

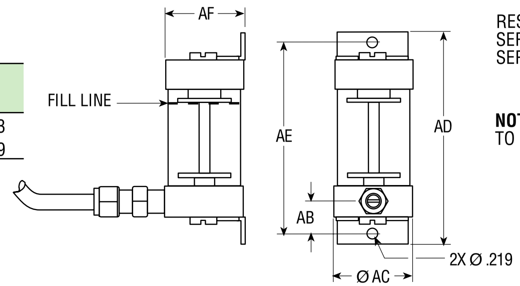
SHAFT KEYWAY: SHOWN AT MID-ROTATION
PORT POSITIONS: INDICATED BY CIRCLED NUMBERS
MTG. HOLES: CENTERED ON CENTERLINE OF ACTUATOR BODY
PLUMBING SCHEMATIC: LOCATED IN ENGINEERING DATA SECTION



METRIC

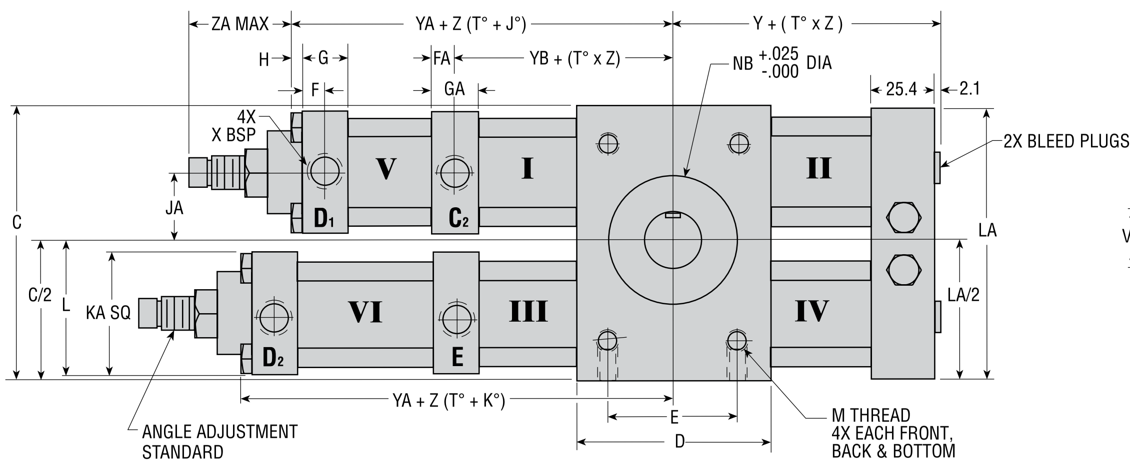
TANK DIMENSIONS

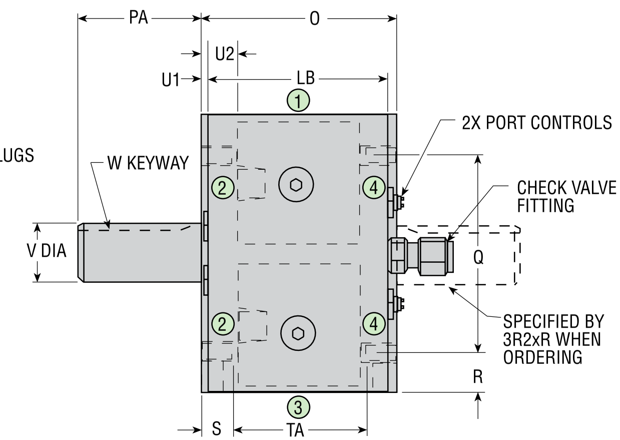
RESERVOIR PART NO.	AB	AC	AD	AE	AF
13459-02-2	16.4	63.5	139.7	130.2	64.3
13459-03-2	13.8	38.1	98.4	88.9	38.9



RESERVIOR ASSEMBLY IS INCLUDED WITH UNIT.
SERIES 2000, 4000, & 6000 UNITS USE PART NO. 68397-03-2.
SERIES 8000 UNITS USE PART NO. 68397-02-2.

NOTE: THE RESERVOIR SHOULD HAVE 1.4 BAR PRESSURE AT ALL TIMES TO ENSURE THE SYSTEM REMAINS PURGED.





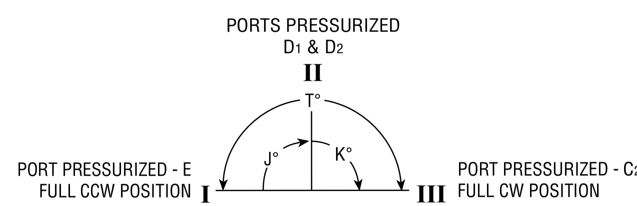
SERIES	LETTER DIMENSION																							IMPERIAL SHAFTS*		METRIC SHAFTS*							
	C	D	E	F	FA	G	GA	H	JA	KA	L	LA	LB	M	NB	O	PA	Q	R	S	TA	U1	U2	V	W	V	W	X	Y	YA	YB	Z	ZA
2000	76	51	38.1	13	13	19	19	0	19	35	36	73.0	44.5	M6 x 1.0 x 8	28.58 x 1.4 DP	50.8	22	50.8	13	6	38.1	3	8	12.69/12.71	3.15 x 1.59 x 16	12.00/11.97	4 x 2.5 x 15	G1/8	85	152	66	0.22	29
4000	108	76	50.8	9	10	17	18	6	29	48	53	106.4	69.9	M8 x 1.25 x 13	50.80 x 1.0 DP	76.2	48	76.2	16	13	50.8	3	14	22.22/22.23	4.75 x 2.36 x 38	22.00/21.96	6 x 3.5 x 32	G1/4	102	171	85	0.33	38
6000	127	102	63.5	10	9	19	18	5	29	57	58	119.1	69.9	M10 x 1.5 x 16	55.00 x 1.3 DP	76.2	48	88.9	19	13	50.8	3	10	28.55/28.58	6.35 x 3.18 x 38	28.00/27.96	8 x 5 x 40	G1/4	118	186	101	0.33	48
8000	203	127	76.2	12	12	27	27	11	48	89	92	155.6	76.2	M20 x 2.5 x 32	85.00 x 3.0 DP	127.0	89	127.0	38	32	63.5	25	19	44.42/44.45	9.53 x 2.36 x 78	44.00/43.96	12 x 5 x 56	G3/8	128	251	133	0.66	73

* BOTH IMPERIAL AND METRIC SHAFT OPTIONS AVAILABLE ON METRIC BODY (IMPERIAL SHAFT = DESIGN 8, AND METRIC SHAFT = DESIGN 9).
NUMBERS FOR METRIC UNITS AND ARE IN mm.

OPTION LOCATION REFERENCE

ACTUATOR TYPE	LETTER OPTION REFERENCED BY TUBE NUMBER							PORT & NEEDLE LOCATIONS REFERENCED BY CIRCLED NUMBERS								
		-D		-P		-M	-E	STANDARD			-T			-I		
	-A	-D1	-D2	-P1	-P2	I & III	I & III	PORT	-P	-D	PORT	-P	-D	PORT	-P	-D
3R1xR & 3R2xR	STANDARD	II	IV	STANDARD		V & VI	V & VI	2	4	4	4	4	4	1 & 3	4	4

SHAFT KEYWAY: SHOWN AT MID-ROTATION
PORT POSITIONS: INDICATED BY CIRCLED NUMBERS
MTG. HOLES: CENTERED ON CENTERLINE OF ACTUATOR BODY
PLUMBING SCHEMATIC: LOCATED IN ENGINEERING DATA SECTION



2000-8000
air/oil tandem

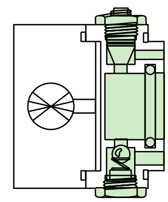
D ADJUSTABLE CUSHIONS BOTH DIRECTIONS

D1 ADJUSTABLE CUSHIONS CLOCKWISE

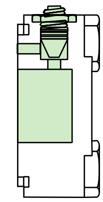
D2 ADJUSTABLE CUSHIONS COUNTERCLOCKWISE

PHD Cushions are designed for smooth deceleration at the end of rotation. When the cushion is activated, the remaining volume in the cylinder must exhaust past an adjustable needle which controls the amount of deceleration. Effective cushion length is approximately 30° of rotation, except on the 8000 Tandem which has 20° of cushion length.

Cushions on Series 2000, 4000, 6000, and 8000 are furnished on one of two racks only.



2000 Cushion Block Style



4000-8000 Poppet Style

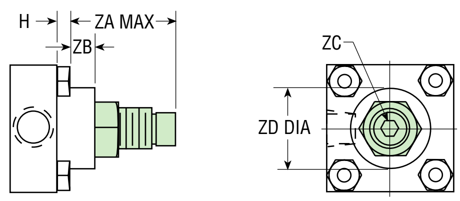
A ANGLE ADJUSTMENT BOTH DIRECTIONS
(Standard on 3-position units)

A1 ANGLE ADJUSTMENT CLOCKWISE

A2 ANGLE ADJUSTMENT COUNTERCLOCKWISE

Adjusting screw(s) for reducing angle of rotation in either or both directions for use where exact degree of desired rotation cannot be predetermined or where requirements may vary during operation. Standard adjusting screw will reduce angle of rotation up to 30°. Available in conjunction with all other optional features.

Cushions are normally engaged over the last 30° of angle. The use of angle adjusting screws to reduce angle of rotation has a direct effect on the length of cushion engagement. Example: 10° angle reduction will reduce cushion engagement by 10°.

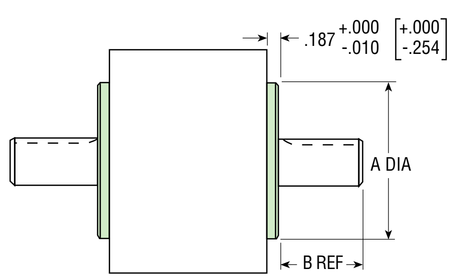


SERIES	LETTER DIMENSION				
	H	ZA	ZB	ZC	ZD
2000	0.00 [0]	1.125 [29]	.312 [8]	3/16 HEX —	.875 [22]
4000	.250 [6]	1.500 [38]	.375 [10]	1/4 HEX —	1.250 [32]
6000	.203 [5]	1.875 [48]	.750 [19]	1/4 HEX —	1.250 [32]
8000	.437 [11]	2.875 [73]	.937 [24]	3/4 FLAT [19 mm]	1.750 [45]

NUMBERS IN [ ] ARE FOR METRIC UNITS AND ARE IN mm.

G SHAFT SEAL COVERS
Not available on Rx9R

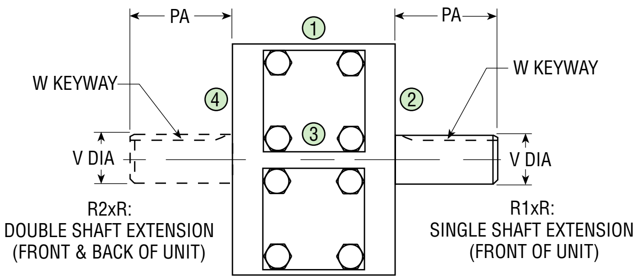
Fits all PHD Series 2000-8000, except when ordering hollow shafts. Isolates internal or external pressures. Maximum pressure differential is 500 psi [34.4 bar]. Furnished installed on actuator only (both sides). Covers are made of hard anodized aluminum. Not to be used as a pilot.



SERIES	LETTER	
	A	B
2000	1.875 [47.63]	.688 [17.5]
4000	3.000 [76.20]	1.688 [42.9]
6000	3.250 [82.55]	1.688 [42.9]
8000	4.480 [113.79]	3.312 [84.1]

NUMBERS IN [ ] ARE FOR METRIC UNITS AND ARE IN mm.

BASIC SHAFT DIMENSIONS: R1xR and R2xR



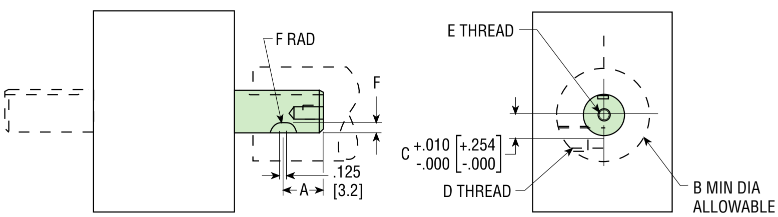
SERIES	LETTER DIMENSION				
	IMPERIAL*			METRIC**	
	PA	V	W	V	W
2000	.875 [22]	.4998/.5003 [12.69/12.71]	1/8 x 1/16 x .625 [3.18 x 1.56 x 16]	— [12.00/11.97]	— [4 x 2.5 x 15]
4000	1.875 [48]	.8748/.8753 [22.22/22.23]	3/16 x 3/32 x 1.500 [4.75 x 2.36 x 38]	— [22.00/21.96]	— [6 x 3.5 x 32]
6000	1.875 [48]	1.124/1.125 [28.55/28.58]	1/4 x 1/8 x 1.500 [6.35 x 3.18 x 38]	— [28.00/27.96]	— [8 x 5 x 40]
8000	3.500 [89]	1.749/1.750 [44.42/44.45]	3/8 x 3/16 x 3.000 [9.53 x 2.36 x 76]	— [44.00/43.96]	— [12 x 5 x 56]

NOTES:
1) **SHAFT KEYWAY:** SHOWN AT MID-ROTATION
2) *IMPERIAL SHAFT UNITS (Rx3R, Rx8R)
3) **METRIC SHAFT UNITS (Rx9R)

K PRELOADED KEYWAY SHAFT

Not available on Rx9R

Required when use of hub adaptor is desired.



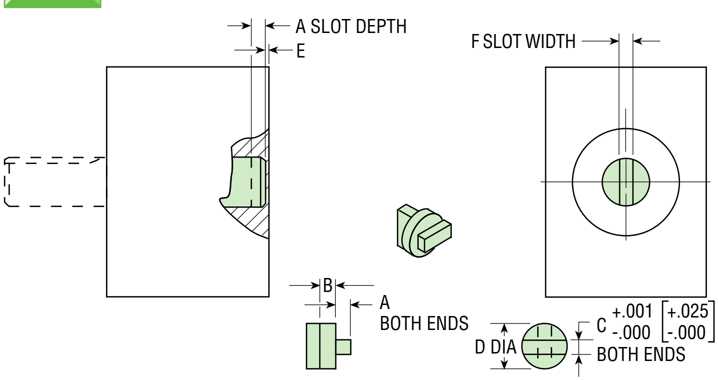
SHAFT KEYWAY: SHOWN AT MID-ROTATION
R2xx UNITS: WHEN ORDERING SPECIFY -K-K FOR PRELOAD ON BOTH SHAFT EXTENSIONS. PRELOAD WILL BE ON OPPOSITE SIDES OF SHAFT.
SET SCREW: INCLUDED WITH UNIT

SERIES	LETTER DIMENSION					
	A	B	C	D	E	F
2000	.375 [9.5]	1.500 [38.1]	.250 [6.35]	3/8-24 [M10]	10-32 x .312 DP [M5 x 8]	.156 [4]
4000	.812 [20.6]	2.000 [50.8]	.437 [11.11]	1/2-20 [M12]	5/16-24 x .440 DP [M8 x 11]	.220 [6]
6000	.812 [20.6]	3.000 [76.2]	.563 [14.28]	5/8-11 [M16]	3/8-24 x .560 DP [M10 x 14]	.251 [6]
8000	1.500 [38.1]	4.000 [101.6]	.875 [22.22]	1-8 [M24]	1/2-20 x .687 DP [M12 x 17.5]	.438 [11]

2000-8000
air/oil tandem

C CROSS KEY SHAFT

Not available on Rx9R

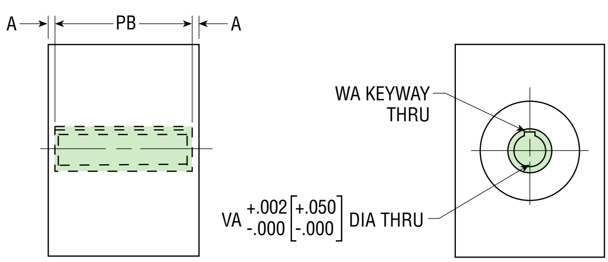


SERIES	LETTER DIMENSION					
	A	B	C	D	E	F
2000	.250 [6.4]	.215 [5.5]	.230 [5.8]	.500 [12.7]	.118 [3]	.250 [6.3]
4000	.250 [6.4]	.265 [6.7]	.248 [6.3]	.875 [22.2]	.120 [3]	.248 [6.3]
6000	.437 [11]	.485 [12.3]	.500 [12.7]	1.125 [28.6]	.150 [3.8]	.5002 [12.7]
8000	.437 [11]	.805 [20.4]	.875 [22.2]	1.750 [44.5]	.245 [6.2]	.8752 [22.2]

SHAFT KEYWAY: SHOWN AT MID-ROTATION
R2xx UNITS: WHEN ORDERING SPECIFY -C-C FOR CROSSKEY ON BOTH SHAFT EXTENSIONS
CROSSKEY: INCLUDED WITH UNIT

H HOLLOW SHAFT

Not available on Rx9R



SERIES	LETTER DIMENSION			
	A	PB	VA	WA
2000	.042 [1.1]	1.920 [48.76]	.250 [6.35]	— —
4000	.042 [1.1]	2.917 [74.09]	.500 [12.7]	1/8 x 1/16 [3.18 x 1.58]
6000	.135 [3.4]	2.730 [69.34]	.687 [17.46]	3/16 x 3/32 [4.76 x 2.38]
8000	.240 [6.1]	4.520 [114.80]	1.125 [28.57]	1/4 x 1/8 [6.35 x 3.18]

SHAFT KEYWAY: SHOWN AT MID-ROTATION

MAGNETIC PISTON FOR USE WITH PHD PROXIMITY SWITCHES

See each data for magnetic piston ordering information.
Switches and brackets must be ordered separately.
See Switches and Sensors section for complete switch information.

E SOLID STATE SWITCHES

Series 2000-8000 Rotary Actuators may be equipped with a magnetic band (specify -E) on the pistons which activates externally mounted PHD Solid State Switches. These switches allow the interfacing of the PHD Actuators to various logic systems. This option is for use with the following switches.

SERIES 1750 SOLID STATE SWITCHES

PART NO.	COLOR	DESCRIPTION
17503-2-06	Yellow	NPN (Sink) Type 4.5-24 VDC, 6 foot cable
17504-2-06	Red	PNP (Source) Type 4.5-24 VDC, 6 foot cable
17523-2	Yellow	NPN (Sink) Type 4.5-24 VDC, Quick Connect
17524-2	Red	PNP (Source) Type 4.5-24 VDC, Quick Connect

SWITCH BRACKETS

	PART NO.
SERIES	SERIES 1750 SWITCH
2000	17000-32-5
4000	17000-34-5
6000	17000-38-0
8000	17000-39-0

M REED SWITCHES

The PHD Magnetic Reed Switches may be used in situations where the Solid State Switches are not applicable. As with the Solid State Switches, a magnetic band (specify -M) on the pistons activates the externally mounted PHD Reed Switches. The Reed Switches may be used to signal a programmable controller, sequencer, relay, or in some cases, a valve solenoid. This option is for use with the following switches.

SERIES 1750 REED SWITCHES

PART NO.	DESCRIPTION	
17502-2-06	White	NPN (Sink) or PNP (Source) 4.5-24 VDC, 6 foot cable
17509-3-06	Green	AC Type 110-120 VAC with Current Limit, 6 foot cable
17522-2	White	NPN (Sink) or PNP (Source) 4.5-24 VDC, Quick Connect
17529-3	Green	AC Type 110-120 VAC, Quick Connect with Current Limit

J SENSOR/SET POINT MODULE

Not available on Rx9R

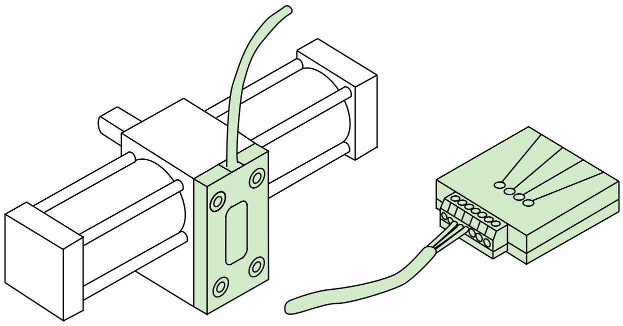
PHD offers a solid state sensor transducer along with a Set Point Module which provides up to four adjustable sensing positions throughout the 180° maximum sensing range. These signals can be used as inputs to a programmable controller to signal ends of rotation in addition to multiple signals during rotation for indication of arc traveled.

The Set Point Module allows independent adjustment of each sensing position and is available for 4.5 to 24 VDC current sinking or current sourcing.

SET POINT MODULE

PART NO.	DESCRIPTION
9800-01-0300	NPN (Sink) 4.5-24 VDC
9800-01-0400	PNP (Source) 4.5-24 VDC

See Switches and Sensors section for information.



L — COUNTERCLOCKWISE UNIDIRECTIONAL CLUTCH

Not available on Rx9R or 7/8000
Output hub will only rotate in counterclockwise direction at specific rotation ordered.

R — CLOCKWISE UNIDIRECTIONAL CLUTCH

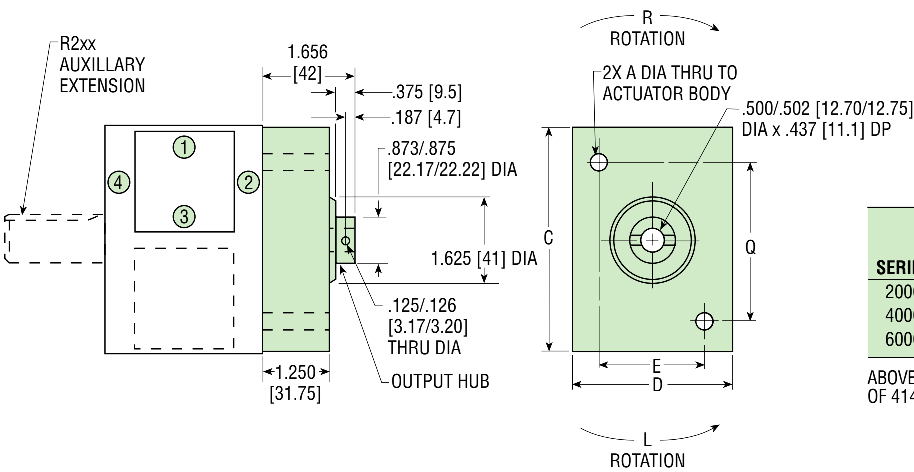
Not available on Rx9R or 7/8000
Output hub will only rotate in clockwise direction at specific rotation ordered.

Overrun clutch for intermittent unidirectional shaft output, available for Series 2000 through 6000.

Output hub rotates in one direction only. It remains motionless while rack and pinion reverse. Clutch repeats within ±1/2°.

Assembly features a Torrington roller clutch. Spring loaded brake shoes limit output shaft free wheeling, but are not intended for stopping external loads.

CAUTION: Any angular error will accumulate; therefore, shot pins or similar locators are necessary on index applications. Maintain shot pin location during reversal of Rotary Actuator to guarantee that clutch shaft does not move due to external forces or slight internal friction in clutch.



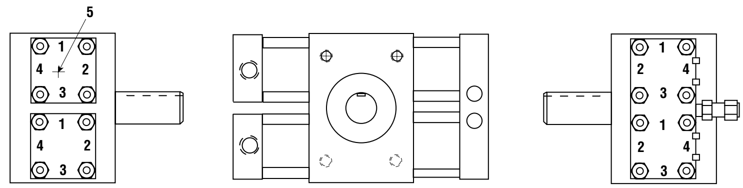
SERIES	LETTER DIMENSION A	C	D	E	Q
2000	.281 [7.2]	2.938 [74.6]	2.000 [51]	1.500 [38]	2.000 [50.8]
4000	.344 [8.7]	4.188 [106.3]	3.000 [76]	2.000 [50.8]	3.000 [76.2]
6000	.406 [10.3]	4.938 [125.4]	4.000 [102]	2.500 [63.5]	3.500 [88.9]

SERIES	LIMITING FACTORS: MAX. INLET PRESSURE(psi)[bar]	MAX. RADIAL OR AXIAL LOAD (lb) [N]
2000	526 [36]	5 [22]
4000	186 [13]	10 [44]
6000	87 [6]	15 [66]

ABOVE INLET PRESSURES PROVIDE A MAXIMUM TORQUE OF 414 in-lb [46.8 Nm] ALLOWED BY THE CLUTCH

PORT & PORT CONTROL® LOCATIONS

Standard port location on all Series 2000-8000 Actuators is position 2. Standard Port Control® and cushion adjustment needles are located in position 4.



I — PORT POSITION 1 TOP RACK PORT POSITION 3 BOTTOM RACK

This option positions the ports in position 1 on tube I and in position 3 on rack III. This allows access to the ports on the "Top" and "Bottom" sides of the actuator.

T — PORT POSITION 4

This option positions the ports in position 4 on tubes I and III.

Y — TANDEM CAP ROTATED 180°

This option rotates the cap of an Air/Oil Tandem Rotary Actuator 180°. This places the Port Control® (and Cushion) needles and the Tandem fitting in position 2. Standard position for these is position 4.

V — FLUORO-ELASTOMER SEALS

Fluoro-Elastomer seals are available for seal compatibility with certain fluids. Seal compatibility should be checked with the fluid manufacturer for proper application. Consult PHD for high temperature applications.

W — CLOSE TOLERANCE ROTATION

Not available on 3 position 3RxxR units

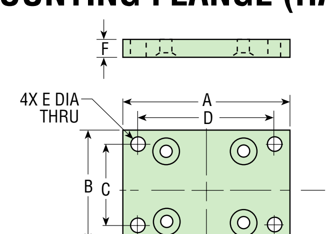
This option may be specified when a precise rotation is required and angle adjustment (see page 5-76) is not acceptable. By specifying this option, rotation will be within a tolerance of +30, -0 minutes. Standard tolerance is -0°, +10° of rotation.

Z1 — ELECTROLESS NICKEL PLATING

Electroless nickel plating is done on all externally exposed ferrous parts except the pinion shaft. This optional plating treatment gives an alternative method of protecting the unit from severe environments.

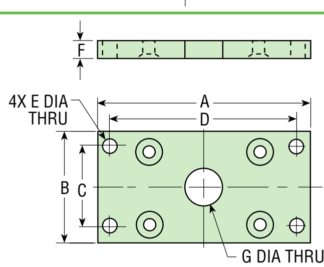
NOTE: Standard plating is Zinc and Black Oxide.

MOUNTING FLANGE (HARDWARE INCLUDED)



BOTTOM MOUNTING FLANGE

SERIES	KIT NO. IMPERIAL	KIT NO. METRIC	LETTER DIMENSION A	B	C	D	E	F
2000	13756	14320	4.250 [108]	2.000 [51]	1.625 [41.3]	2.625 [66.7]	.281 [7.1]	.250 [6.3]
4000	13757	14321	4.500 [114]	3.000 [76]	2.375 [60.3]	3.875 [98.4]	.406 [10.3]	.437 [11.1]
6000	13758	14322	4.500 [114]	4.000 [102]	3.375 [85.7]	3.875 [98.4]	.406 [10.3]	.437 [11.1]



SIDE MOUNTING FLANGE

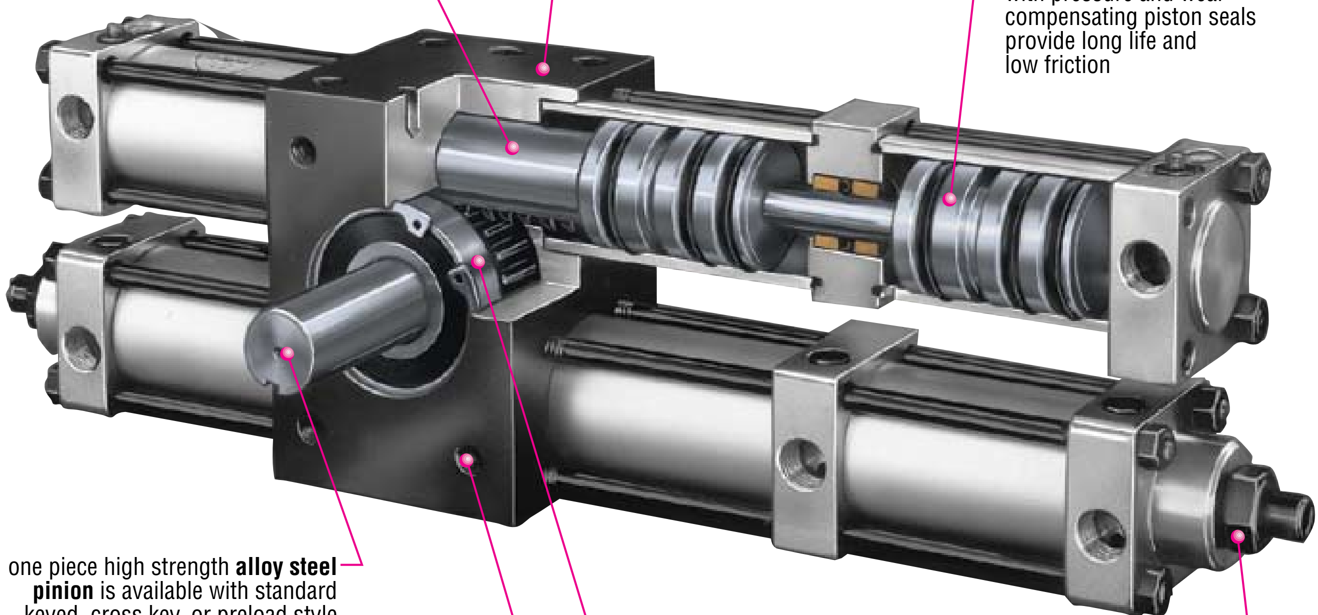
SERIES	KIT NO. IMPERIAL	KIT NO. METRIC	LETTER DIMENSION A	B	C	D	E	F	G
2000	13759	14316	4.250 [108]	2.000 [51]	1.375 [34.9]	3.625 [92.1]	.281 [7.1]	.250 [6.3]	.625 [15.9]
4000	13760	14317	5.750 [146]	3.000 [76]	2.125 [54.0]	5.125 [130.2]	.406 [10.3]	.437 [11.1]	1.000 [25.4]
6000	13761	14318	6.500 [165]	4.000 [102]	3.375 [85.7]	5.875 [149.2]	.406 [10.3]	.437 [11.1]	1.250 [31.8]
8000	13762	14319	12.000 [305]	5.000 [127]	3.000 [76.2]	10.000 [254.0]	.781 [19.8]	.750 [19.1]	1.875 [47.6]

All dimensions are reference only unless specifically toleranced.

2000-8000 multi-position

THREE, FOUR, OR FIVE ROTARY POSITIONS

4 POSITION UNIT



Cutaway unit shown above does not represent a standard 4 position unit. (No stop tubes are shown, -A caps are not located on proper caps and out tubes are on wrong side of unit)

Major Benefits

- Three, four, or five rotary positions

Industry Uses

- Automotive
- General industrial machines

ORDERING DATA: MULTI-POSITION ROTARY ACTUATORS

TO ORDER SPECIFY:
No. of Rotary Positions, Type, Design No., Fluid Media, Series, and Options.

5 | R1 | 1 | A | 4 | 180 - 45 - 90 - 135 - P-D

NO. OF ROTARY POSITIONS
3 - 3 Position
4 - 4 Position
5 - 5 Position

TYPE
R1 - Single Shaft
R2 - Double Shaft

DESIGN NO.
1 - Imperial
5 - Metric - Port and mounting metric. Pinion and keyways are imperial.
6 - Metric Complete

FLUID MEDIA
A - Pneumatic
H - Hydraulic

SERIES
2 (000) 1" Bore Double Rack
4 (000) 1-3/8" Bore Double Rack
6 (000) 2" Bore Double Rack
8 (000) 3" Bore Double Rack
NOTE: 2000 Series available in 3 Position only.

TOTAL ANGLE OF ROTATION STANDARD ANGLES

ANGLE OF ROTATION FROM POSITION I TO POSITION II

ANGLE OF ROTATION FROM POSITION I TO POSITION III. USED ON 4 & 5 POSITION ONLY.

ANGLE OF ROTATION FROM POSITION I TO POSITION IV. USED ON 5 POSITION ONLY.

STANDARD OPTIONS
B - Shock Pads on extreme positions (not available on hydraulic units)
D - Cushions on extreme positions
E - Magnetic Piston for Solid State Switch
I - Port Position 1 on top rack
Port Position 3 on bottom rack
M - Magnetic Piston for Reed Switch
P - Port Controls® on all caps
T - Port in Position 4
V - Fluoro-Elastomer Seals
Z1 - Electroless Nickel Plate

DESIGN NO. 1 AND 5 OPTIONS ONLY
C - Cross Key Pinion Shaft
G - Shaft Seal both sides
H - Hollow Pinion Shaft (not available on type R2 units)
J - Hall Sensor for rotations not exceeding 180° (Set Point Module is ordered separately)
K - Preload Keyway Pinion Shaft (required for use with hub adaptors)

NOTES:
1) Angle Adjustments are standard on all Multi-Position Rotary Actuators.
2) Sensor must be used with a PHD Set Point Module. See Switches and Sensors section for information and ordering data.

PROXIMITY SWITCH MOUNTING BRACKETS

SERIES	SIZE NO.
2000	32
4000	34
6000	38
8000	39

See Switches and Sensors section for complete ordering information.

Options may affect unit length. See unit dimension and options pages for adders.

UNIQUE ROTARY ACTUATORS ARE AVAILABLE. SEE UNIQUE PRODUCTS AT THE END OF THIS SECTION.

SPECIFICATIONS	MULTI-POSITION SERIES 2000-8000
PNEUMATIC OPERATING PRESSURE	20 to 150 psi [1.4 to 10 bar]
HYDRAULIC OPERATING PRESSURE**	40 to 1500 psi [2.8 to 103 bar] (see option table below)
OPERATING TEMPERATURE	-20° to 180° F [-29° to 82° C]
FULL (TOTAL) ROTATIONAL TOLERANCE	Nominal rotation +10°/-0°
MID-POSITION ROTATIONAL TOLERANCES (ALL MID-POSITIONS 2, 3, 4)	(see chart below for mid-position tolerance)
BACKLASH	
AT ANY MID-ROTATION POINT, ALL UNITS AND 4 POSITION, END OF ROTATIONS	1° (2000), 0° 30' (4000, 6000), 0° 15' (8000)
AT END OF ROTATIONS ON 3 AND 5 POSITIONS*	0° (2000, 4000, 6000, 8000)
AT MID-POSITION LOCATIONS (ALL MID-POSITIONS 2, 3, 4)	(see chart below for mid-position backlash)
LUBRICATION	Factory lubricated for rated life
MAINTENANCE	Field repairable

NOTE: *Angle adjustment screw must be engaged or adjusted to achieve 0° backlash.

SIZE	BORE DIAMETER in	BORE DIAMETER mm	DISPLACEMENT VOLUME/DEG $in^3/°$	DISPLACEMENT VOLUME/DEG $cm^3/°$	THEORETICAL TORQUE OUTPUT in-lb/psi	THEORETICAL TORQUE OUTPUT Nm/bar	MAX AXIAL BEARING LOAD lb	MAX AXIAL BEARING LOAD N	MAX RADIAL BEARING LOAD lb	MAX RADIAL BEARING LOAD N	DISTANCE BETWEEN SHAFT BEARINGS in	DISTANCE BETWEEN SHAFT BEARINGS mm
2000	1.000	25.4	.014	.229	.39	.64	120	534	300	1334	1.375	34.9
4000	1.375	34.9	.038	.623	1.11	1.82	240	1068	600	2669	2.188	55.6
6000	2.000	50.8	.082	13.44	2.36	3.87	370	1646	925	4114	2.235	56.8
8000	3.000	76.2	.370	6.06	10.60	17.37	800	3558	2000	8896	3.750	95.3

PRESSURE RATINGS FOR OPTIONS

All pneumatic rotary actuators have a maximum pressure rating of 150 psi [10 bar] air. Most hydraulic rotary actuators have a maximum pressure rating of 1500 psi [100 bar], except as noted in chart below.

HYD SERIES	OPTION psi [bar] -P		-D		-E OR -M	
2000	–	–	–	–	–	–
4000	–	–	–	–	–	–
6000	–	–	–	–	750	[52]
8000	–	–	–	–	500	[35]

NOTE: All hydraulic ratings are based on non-shock hydraulic service.

Minimum factor of safety at maximum rated hydraulic pressure for output shaft is 2:1, and for hydraulic chambers is 3:1. Consult PHD for proof of pressure data. All ratings based on non-shock hydraulic service and with full rotation tubes not being double powered.

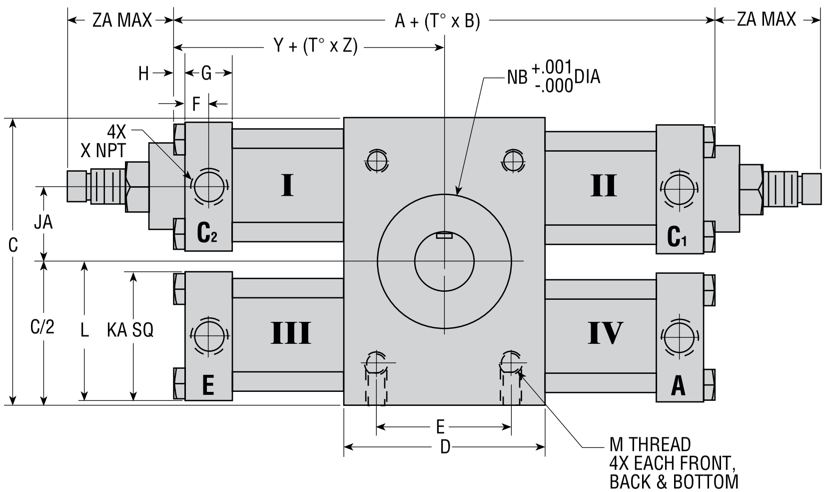
BACKLASH & INTERMEDIATE POSITION TOLERANCES

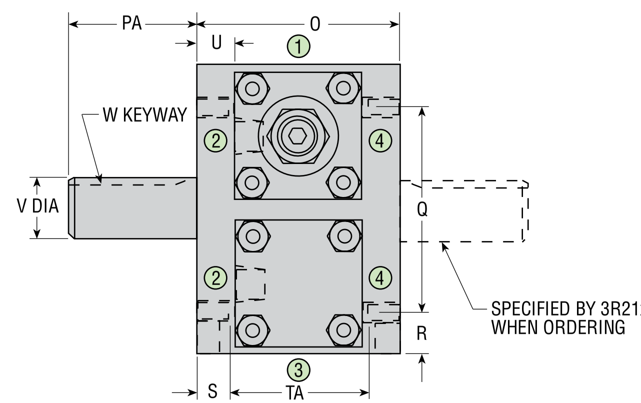
SERIES	ROTATIONAL TOLERANCE**	BACKLASH
2000	±1°	1° 30'
4000 & 6000	±0° 30'	1° 15'
8000	±0° 15'	1°

**Rotational position from one intermediate position to another (measured at centers of backlash).

SIZING AND APPLICATION ASSISTANCE
See PHD Product Sizing Catalog for specific and complete sizing information.
Online sizing assistance is available at: ***www.phdinc.com/apps/sizing***

IMPERIAL





CAP STYLE	SERIES	A	B	C	D	E	F	G	H	JA	KA	L	M	NB	O	PA	Q	R	S	TA	U	V	W	X	Y	Z	ZA
		LETTER DIMENSION																									
PLAIN	2000	5.698	.0174	3.000	2.000	1.500	.250	.500	0.00	.750	1.375	1.437	1/4-20 x .312 DP	1.125 x .056 DP	2.000	.875	2.000	.500	.250	1.500	.312	.4998/.5003	1/8 x 1/16 x .625	1/8	2.849	.0087	0
-A	2000	6.198	.0174	3.000	2.000	1.500	.500	.750	0.00	.750	1.375	1.437	1/4-20 x .312 DP	1.125 x .056 DP	2.000	.875	2.000	.500	.250	1.500	.312	.4998/.5003	1/8 x 1/16 x .625	1/8	3.099	.0087	1.125
BOTH	4000	7.906	.026	4.250	3.000	2.000	.344	.688	.250	1.156	1.875	2.094	5/16-18 x .500 DP	2.000 x .039 DP	3.000	1.875	3.000	.625	.500	2.000	.562	.8748/.8753	3/16 x 3/32 x 1.500	1/4	3.953	.013	1.500
BOTH	6000	9.126	.026	5.000	4.000	2.500	.375	.750	.203	1.156	2.250	2.281	3/8-16 x .625 DP	2.1654 x .052 DP	3.000	1.875	3.500	.750	.500	2.000	.375	1.124/1.125	1/4 x 1/8 x 1.500	1/4	4.563	.013	1.875
BOTH	8000	12.160	.052	8.000	5.000	3.000	.469	1.062	.437	1.875	3.500	3.625	3/4-10 x 1.250 DP	3.3465 x .120 DP	5.000	3.500	5.000	1.500	1.250	2.500	.750	1.749/1.750	3/8 x 3/16 x 3.000	3/8	6.080	.026	2.875

OPTION LOCATION REFERENCE

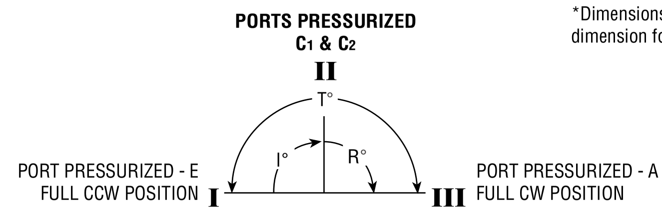
ACTUATOR TYPE	LETTER OPTION REFERENCED BY TUBE NUMBER						PORT & NEEDLE LOCATIONS REFERENCED BY CIRCLED NUMBERS								
							STANDARD			-T			-I		
	-A	-B	-D	-P	-M	-E	PORT	-P	-D	PORT	-P	-D	PORT	-P	-D
3R11A & 3R21A	STANDARD	I & II	I & II	ALL	ALL	ALL	2	1 & 3	1	4	1 & 3	1	1 & 3	4	4
3R11H & 3R21H	STANDARD	N/A	I & II	ALL	ALL	ALL	2	1 & 3	1	4	1 & 3	1	1 & 3	4	4

QUICK REFERENCE FOR: A + (T° x B)

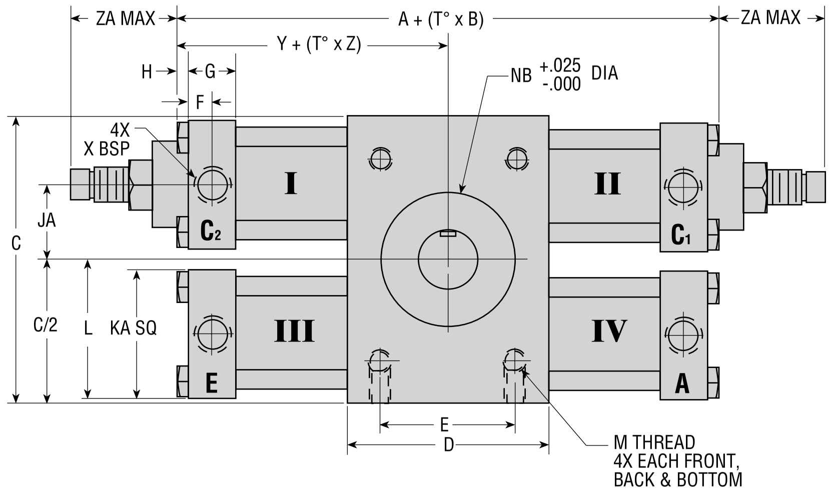
SERIES	DEGREE OF ROTATION					
	45	90	180	270	360	450
*2000	6.481	7.264	8.830	10.396	11.962	13.528
4000	9.076	10.246	12.586	14.926	17.266	19.606
6000	10.296	11.466	13.806	16.146	18.486	20.826
8000	14.500	16.840	21.520	26.200	30.880	35.560

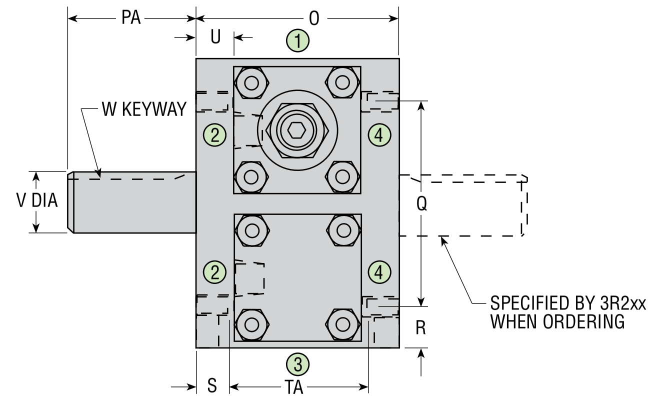
*Dimensions calculated using plain cap style. Add .250 to dimension for each -A style cap used on Series 2000 only.

SHAFT KEYWAY: SHOWN AT MID-ROTATION
PORT POSITIONS: INDICATED BY CIRCLED NUMBERS
CUSHIONS: SERIES 2000 ACTUATORS:
ADD 1/2" TO RESPECTIVE "A" AND "Y" DIMENSION FOR EACH CUSHION
MTG. HOLES: CENTERED ON CENTERLINE OF ACTUATOR BODY
STOP TUBES: LOCATED IN TUBES I & II
PLUMBING SCHEMATIC: LOCATED IN PHD PRODUCT SIZING CATALOG



METRIC





CAP STYLE	SERIES	A	B	C	D	E	F	G	H	JA	KA	L	M	NB	O	PA	Q	R	S	TA	U	IMPERIAL SHAFTS* V	IMPERIAL SHAFTS* W	METRIC SHAFTS* V	METRIC SHAFTS* W	X	Y	Z	ZA
PLAIN	2000	145	0.44	76	51	38.1	6	13	0	19	35	36	M6 x 1.0 x 8	28.58 x 1.4 DP	50.8	22	50.8	13	6	38.1	8	12.69/12.71	3.15 x 1.59 x 16	12.00/11.97	4 x 2.5 x 15	G1/8	72	0.22	0
-A	2000	157	0.44	76	51	38.1	13	19	0	19	35	36	M6 x 1.0 x 8	28.58 x 1.4 DP	50.8	22	50.8	13	6	38.1	8	12.69/12.71	3.15 x 1.59 x 16	12.00/11.97	4 x 2.5 x 15	G1/8	78	0.22	29
BOTH	4000	201	0.66	108	76	50.8	9	17	6	29	48	53	M8 x 1.25 x 13	50.80 x 1.0 DP	76.2	48	76.2	16	13	50.8	14	22.22/22.23	4.75 x 2.36 x 38	22.00/21.96	6 x 3.5 x 32	G1/4	100	0.33	38
BOTH	6000	232	0.66	127	102	63.5	10	19	5	29	57	58	M10 x 1.5 x 16	55.00 x 1.3 DP	76.2	48	88.9	19	13	50.8	10	28.55/28.58	6.35 x 3.18 x 38	28.00/27.96	8 x 5 x 40	G1/4	116	0.33	48
BOTH	8000	309	1.32	203	127	76.2	12	27	11	48	89	92	M20 x 2.5 x 32	85.00 x 3.0 DP	127.0	89	127.0	38	32	63.5	19	44.42/44.45	9.53 x 2.36 x 78	44.00/43.96	12 x 5 x 56	G3/8	154	0.66	73

(Columns A through ZA are under LETTER DIMENSION.)

* BOTH IMPERIAL AND METRIC SHAFT OPTIONS AVAILABLE ON METRIC BODY (IMPERIAL SHAFT = DESIGN 5, AND METRIC SHAFT = DESIGN 6).
NUMBERS FOR METRIC UNITS AND ARE IN mm.

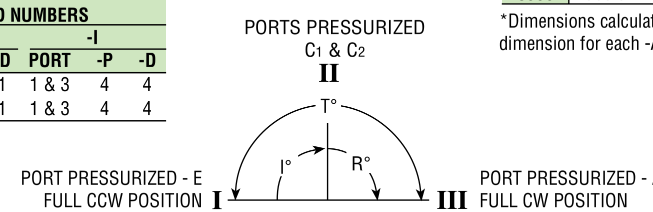
QUICK REFERENCE FOR: A + (T° x B)

SERIES	DEGREE OF ROTATION 45	90	180	270	360	450
*2000	164.6	184.5	224.2	264.1	303.8	343.6
4000	230.5	260.2	319.8	379.1	438.6	498.0
6000	261.5	291.1	410.8	350.7	469.5	529.0
8000	368.3	427.7	539.6	546.6	784.4	903.2

*Dimensions calculated using plain cap style. Add 6.3 to dimension for each -A style cap used on Series 2000 only.

OPTION LOCATION REFERENCE

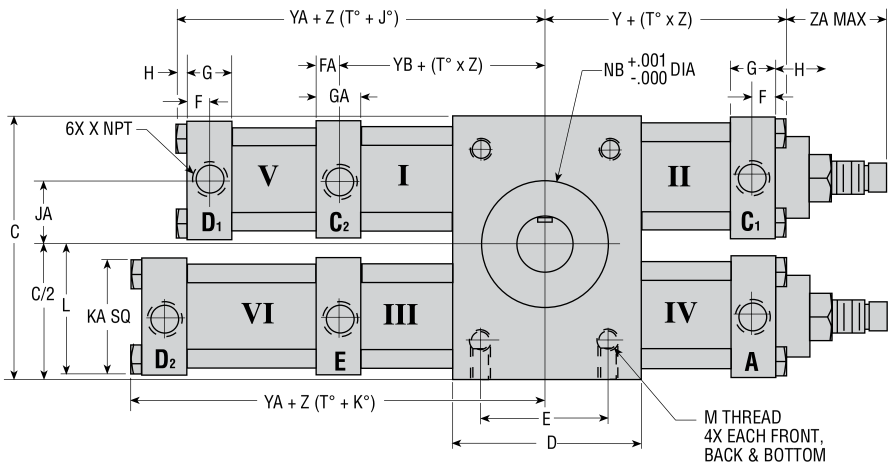
ACTUATOR TYPE	LETTER OPTION REFERENCED BY TUBE NUMBER -A	-B	-D	-P	-M	-E	PORT & NEEDLE LOCATIONS REFERENCED BY CIRCLED NUMBERS: STANDARD PORT	STANDARD -P	STANDARD -D	-T PORT	-T -P	-T -D	-I PORT	-I -P	-I -D
3R1xA & 3R2xA	STANDARD	I & II	I & II	ALL	ALL	ALL	2	1 & 3	1	4	1 & 3	1	1 & 3	4	4
3R1xH & 3R2xH	STANDARD	N/A	I & II	ALL	ALL	ALL	2	1 & 3	1	4	1 & 3	1	1 & 3	4	4

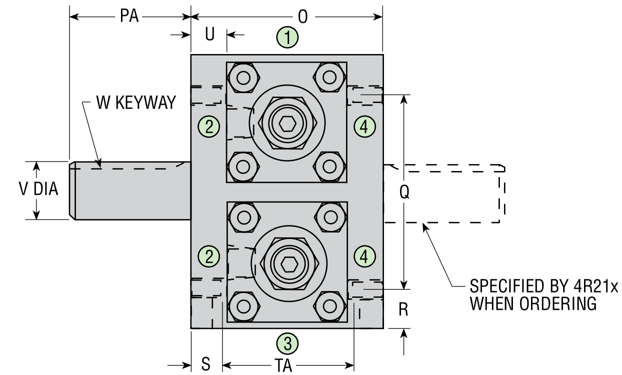


SHAFT KEYWAY: SHOWN AT MID-ROTATION
PORT POSITIONS: INDICATED BY CIRCLED NUMBERS
CUSHIONS: SERIES 2000 ACTUATORS:
ADD 13.0 mm TO RESPECTIVE "A" AND "Y" DIMENSION FOR EACH CUSHION
MTG. HOLES: CENTERED ON CENTERLINE OF ACTUATOR BODY
STOP TUBES: LOCATED IN TUBES I & II
PLUMBING SCHEMATIC: LOCATED IN PHD PRODUCT SIZING CATALOG.

DIMENSIONS: 4 POSITION ROTARY ACTUATORS

IMPERIAL



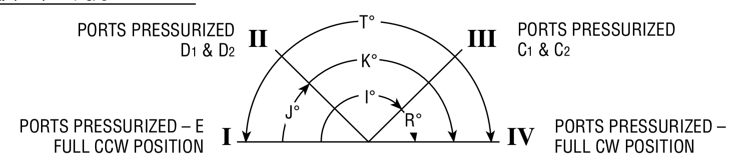


SERIES	C	D	E	F	FA	G	GA	H	JA	KA	L	M	NB	O	PA	Q	R	S	TA	U	V	W	X	Y	YA	YB	Z	ZA
	LETTER DIMENSION																											
4000	4.250	3.000	2.000	.344	.375	.688	.719	.250	1.156	1.875	2.094	5/16-18 x .500 DP	2.000 x .039	3.000	1.875	3.000	.625	.500	2.000	.562	.8748/.8753	3/16 x 3/32 x 1.500	1/4	3.953	6.721	3.360	.013	1.500
6000	5.000	4.000	2.500	.375	.344	.750	.719	.203	1.156	2.250	2.281	3/8-16 x .625 DP	2.1654 x .052	3.000	1.875	3.500	.750	.500	2.000	.375	1.124/1.125	1/4 x 1/8 x 1.500	1/4	4.563	7.325	3.980	.013	1.875
8000	8.000	5.000	3.000	.469	.469	1.062	1.062	.437	1.875	3.500	3.625	3/4-10 x 1.250 DP	3.3465 x .120	5.000	3.500	5.000	1.500	1.250	2.500	.750	1.749/1.750	3/8 x 3/16 x 3.000	3/8	6.080	9.865	5.236	.026	2.875

OPTION LOCATION REFERENCE

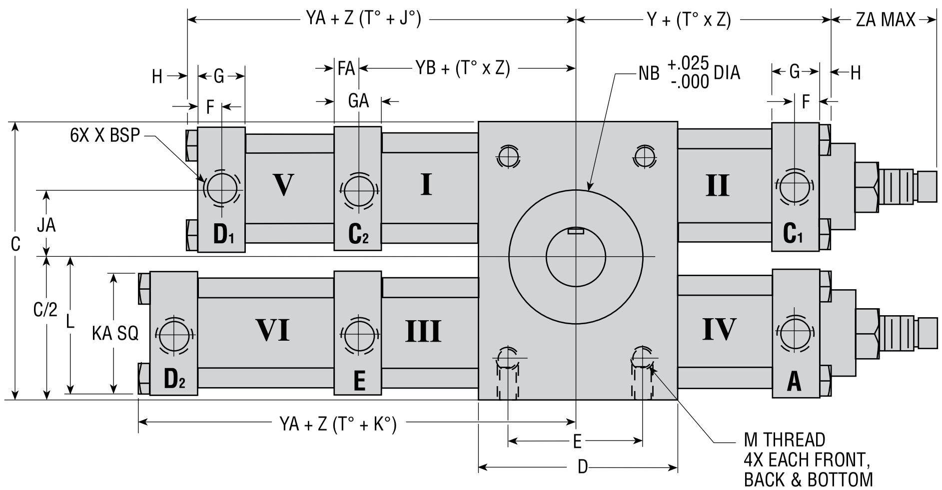
ACTUATOR TYPE	LETTER OPTION REFERENCED BY TUBE NUMBER						PORT & NEEDLE LOCATIONS REFERENCED BY CIRCLED NUMBERS											
							STANDARD			-T			-I			-I		
	-A	-B	-D	-P	-M	-E	PORT	-P	-D	PORT	-P	-D	PORT	-P	-D	PORT	-P	-D
4R11A & 4R21A	STANDARD	II & IV	II & IV	ALL	ALL	ALL	2	1 & 3	1 & 3	4	1 & 3	1 & 3	1 & 3	2 & 4	4	1 & 3	4	4
4R11H & 4R21H	STANDARD	N/A	II & IV	ALL	ALL	ALL	2	1 & 3	1 & 3	4	1 & 3	1 & 3	1 & 3	2 & 4	4	1 & 3	4	4

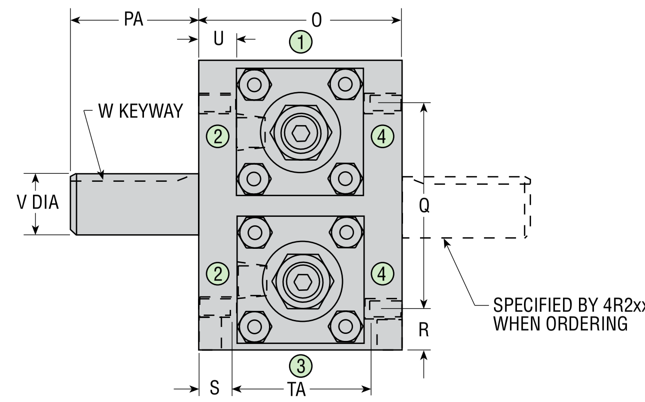
SHAFT KEYWAY: SHOWN AT MID-ROTATION
PORT POSITIONS: INDICATED BY CIRCLED NUMBERS
MTG. HOLES: CENTERED ON CENTERLINE OF ACTUATOR BODY
STOP TUBES: LOCATED IN TUBES I & II
PLUMBING SCHEMATIC: LOCATED IN PHD PRODUCT SIZING CATALOG



All dimensions are reference only unless specifically toleranced.

METRIC



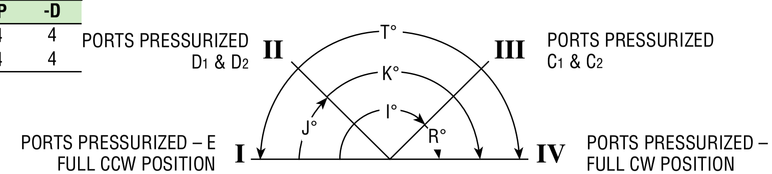


SERIES	LETTER DIMENSION																													
																					IMPERIAL SHAFTS*		METRIC SHAFTS*							
	C	D	E	F	FA	G	GA	H	JA	KA	L	M	NB	O	PA	Q	R	S	TA	U	V	W	V	W	X	Y	YA	YB	Z	ZA
4000	108	76	50.8	9	10	17	18	6	29	48	53	M8 x 1.25 x 13	50.80 x 1.0 DP	76.2	48	76.2	16	13	50.8	14	22.22/22.23	4.75 x 2.36 x 38	22.00/21.96	6 x 3.5 x 32	G1/4	100	171	85	0.33	38
6000	127	102	63.5	10	9	19	18	5	29	57	58	M10 x 1.5 x 16	55.00 x 1.3 DP	76.2	48	88.9	19	13	50.8	10	28.55/28.58	6.35 x 3.18 x 38	28.00/27.96	8 x 5 x 40	G1/4	116	186	101	0.33	48
8000	203	127	76.2	12	12	27	27	11	48	89	92	M20 x 2.5 x 32	85.00 x 3.0 DP	127.0	89	127.0	38	32	63.5	19	44.42/44.45	9.53 x 2.36 x 78	44.00/43.96	12 x 5 x 56	G3/8	154	251	133	0.66	73

* BOTH IMPERIAL AND METRIC SHAFT OPTIONS AVAILABLE ON METRIC BODY (IMPERIAL SHAFT = DESIGN 5, AND METRIC SHAFT = DESIGN 6). NUMBERS FOR METRIC UNITS AND ARE IN mm.

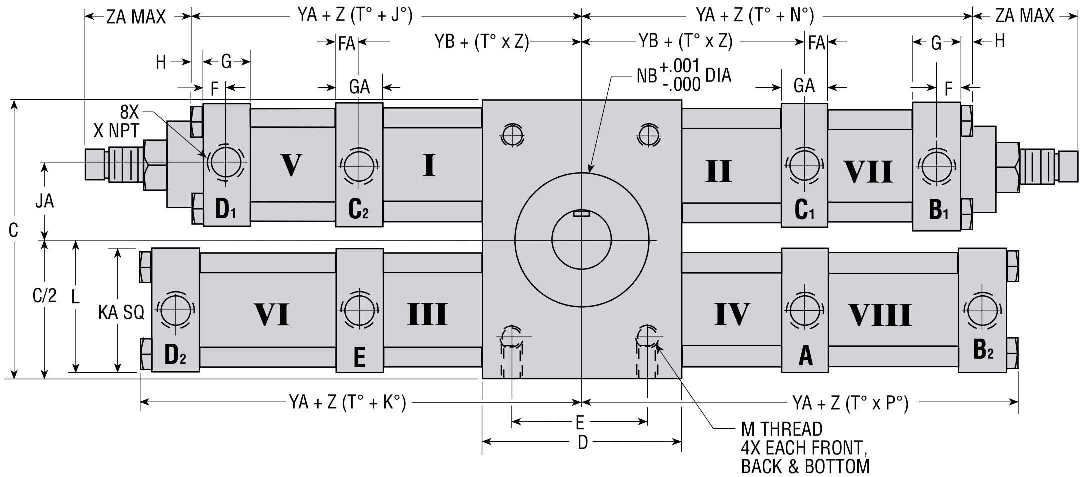
OPTION LOCATION REFERENCE

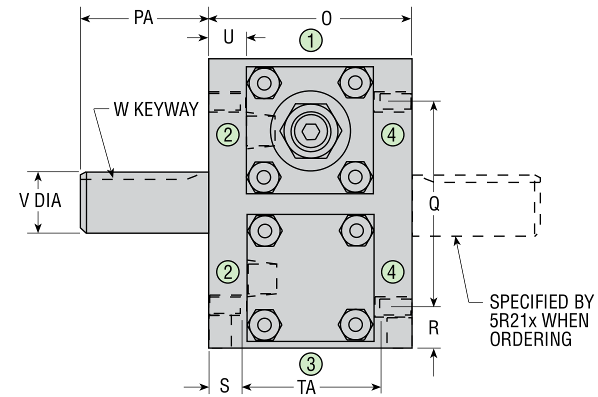
ACTUATOR TYPE	LETTER OPTION REFERENCED BY TUBE NUMBER						PORT & NEEDLE LOCATIONS REFERENCED BY CIRCLED NUMBERS								
							STANDARD			-T			-I		
	-A	-B	-D	-P	-M	-E	PORT	-P	-D	PORT	-P	-D	PORT	-P	-D
4R1xA & 4R2xA	STANDARD	II & IV	II & IV	ALL	ALL	ALL	2	1 & 3	1 & 3	4	1 & 3	1 & 3	1 & 3	4	4
4R15xH & 4R2xH	STANDARD	N/A	II & IV	ALL	ALL	ALL	2	1 & 3	1 & 3	4	1 & 3	1 & 3	1 & 3	4	4



SHAFT KEYWAY: SHOWN AT MID-ROTATION
PORT POSITIONS: INDICATED BY CIRCLED NUMBERS
MTG. HOLES: CENTERED ON CENTERLINE OF ACTUATOR BODY
STOP TUBES: LOCATED IN TUBES I & II
PLUMBING SCHEMATIC: LOCATED IN PHD PRODUCT SIZING CATALOG.

IMPERIAL



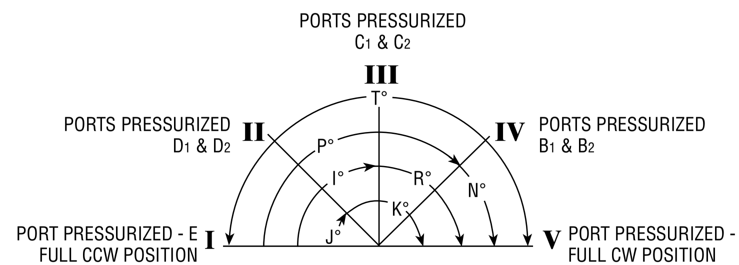


SERIES	LETTER DIMENSION																									
	C	D	E	F	FA	G	GA	H	JA	KA	L	M	NB	O	PA	Q	R	S	TA	U	V	W	X	YA	YB	Z	ZA
4000	4.250	3.000	2.000	.344	.375	.688	.719	.250	1.156	1.875	2.094	5/16-18 x .500 DP	2.000 x .039 DP	3.000	1.875	3.000	.625	.500	2.000	.562	.8748/.8753	3/16 x 3/32 x 1.500	1/4	6.721	3.360	.013	1.500
6000	5.000	4.000	2.500	.375	.344	.750	.719	.203	1.156	2.250	2.281	3/8-16 x .625 DP	2.1654 x .052 DP	3.000	1.875	3.500	.750	.500	2.000	.375	1.124/1.125	1/4 x 1/8 x 1.500	1/4	7.325	3.980	.013	1.875
8000	8.000	5.000	3.000	.469	.469	1.062	1.062	.437	1.875	3.500	3.625	3/4-10 x 1.250 DP	3.3465 x .120 DP	5.000	3.500	5.000	1.500	1.250	2.500	.750	1.749/1.750	3/8 x 3/16 x 3.000	3/8	9.865	5.236	.026	2.875

OPTION LOCATION REFERENCE

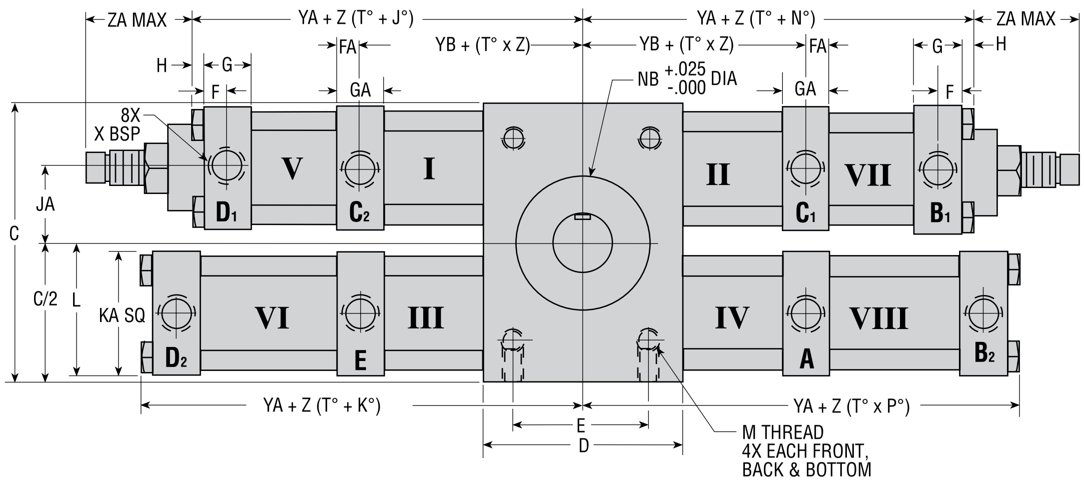
ACTUATOR TYPE	LETTER OPTION REFERENCED BY TUBE NUMBER						PORT & NEEDLE LOCATIONS REFERENCED BY CIRCLED NUMBERS								
							STANDARD			-T			-I		
	-A	-B	-D	-P	-M	-E	PORT	-P	-D	PORT	-P	-D	PORT	-P	-D
5R11A & 5R21A	STANDARD	VII & V	VII & V	ALL	ALL	ALL	2	1 & 3	1	4	1 & 3	1	1 & 3	4	4
5R11H & 5R21H	STANDARD	N/A	VII & V	ALL	ALL	ALL	2	1 & 3	1	4	1 & 3	1	1 & 3	4	4

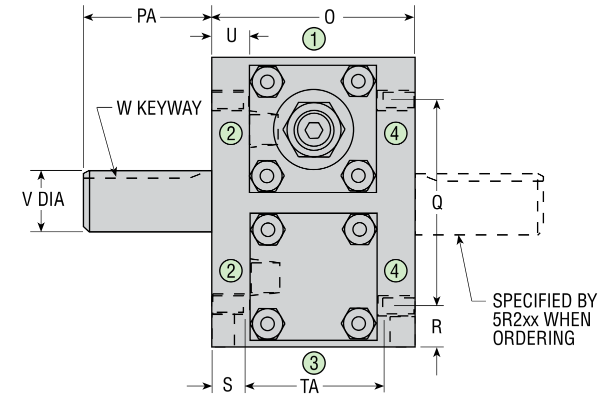
SHAFT KEYWAY: SHOWN AT MID-ROTATION
PORT POSITIONS: INDICATED BY CIRCLED NUMBERS
MTG. HOLES: CENTERED ON CENTERLINE OF ACTUATOR BODY
STOP TUBES: LOCATED IN TUBES I & II
PLUMBING SCHEMATIC: LOCATED IN PHD PRODUCT SIZING CATALOG



All dimensions are reference only unless specifically toleranced.

METRIC





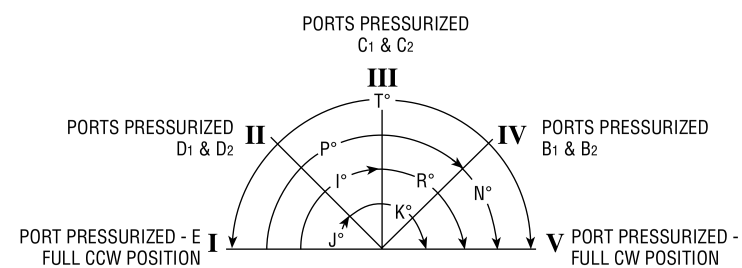
SERIES	C	D	E	F	FA	G	GA	H	JA	KA	L	M	NB	O	PA	Q	R	S	TA	U	IMPERIAL SHAFTS* V	IMPERIAL SHAFTS* W	METRIC SHAFTS* V	METRIC SHAFTS* W	X	YA	YB	Z	ZA
4000	108	76	50.8	9	10	17	18	6	29	48	53	M8 x 1.25 x 13	50.80 x 1.0 DP	76.2	48	76.2	16	13	50.8	14	22.22/22.23	4.75 x 2.36 x 38	22.00/21.96	6 x 3.5 x 32	G1/4	171	85	0.33	38
6000	127	102	63.5	10	9	19	18	5	29	57	58	M10 x 1.5 x 16	55.00 x 1.3 DP	76.2	48	88.9	19	13	50.8	10	28.55/28.58	6.35 x 3.18 x 38	28.00/27.96	8 x 5 x 40	G1/4	186	101	0.33	48
8000	203	127	76.2	12	12	27	27	11	48	89	92	M20 x 2.5 x 32	85.00 x 3.0 DP	127.0	89	127.0	38	32	63.5	19	44.42/44.45	9.53 x 2.36 x 78	44.00/43.96	12 x 5 x 56	G3/8	251	133	0.66	73

* BOTH IMPERIAL AND METRIC SHAFT OPTIONS AVAILABLE ON METRIC BODY (IMPERIAL SHAFT = DESIGN 5, AND METRIC SHAFT = DESIGN 6).
NUMBERS FOR METRIC UNITS AND ARE IN mm.

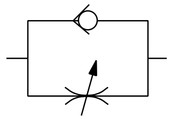
OPTION LOCATION REFERENCE

ACTUATOR TYPE	LETTER OPTION REFERENCED BY TUBE NUMBER						PORT & NEEDLE LOCATIONS REFERENCED BY CIRCLED NUMBERS								
							STANDARD			-T			-I		
	-A	-B	-D	-P	-M	-E	PORT	-P	-D	PORT	-P	-D	PORT	-P	-D
5R1xA & 5R2xA	STANDARD	VII & V	VII & V	ALL	ALL	ALL	2	1 & 3	1	4	1 & 3	1	1 & 3	4	4
5R1xH & 5R2xH	STANDARD	N/A	VII & V	ALL	ALL	ALL	2	1 & 3	1	4	1 & 3	1	1 & 3	4	4

SHAFT KEYWAY: SHOWN AT MID-ROTATION
PORT POSITIONS: INDICATED BY CIRCLED NUMBERS
MTG. HOLES: CENTERED ON CENTERLINE OF ACTUATOR BODY
STOP TUBES: LOCATED IN TUBES I & II
PLUMBING SCHEMATIC: LOCATED IN PHD PRODUCT SIZING CATALOG



P PORT CONTROL®



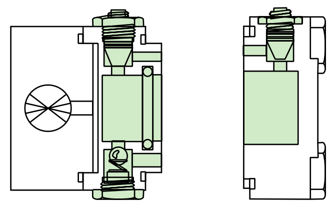
The exclusive PHD Port Control®, "built-in" speed control valve, based on the "meter-out" principle, features an adjustable needle and a separate ball check. Both are built into the rotary actuator end cap and are used to control the speed of the actuator over its entire rotation.

The self-locking needle has micrometer threads and is adjustable under pressure. It determines the orifice size which controls the exhaust volume only of the actuator proper. The separate ball check is closed while fluid is exhausting from the actuator, but opens to permit full flow of incoming fluids. The PHD Port Control® provides the optimum in speed control for rotary actuators. It saves space and eliminates the cost of fittings and installation for external flow control valves.

D ADJUSTABLE CUSHIONS

PHD Cushions are designed for smooth deceleration at the end of rotation. When the cushion is activated, the remaining volume in the cylinder must exhaust past an adjustable needle which controls the amount of deceleration. Effective cushion length is approximately 30° of rotation.

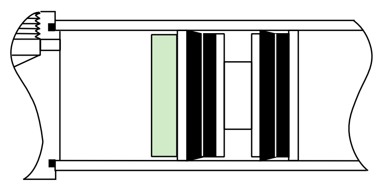
Cushions on Series 2000, 4000, 6000 and 8000 are furnished on one of two racks only.



2000 Cushion Block Style 4000-8000 Poppet Style

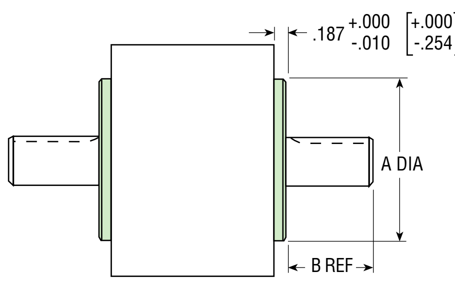
B SHOCK PADS

Polyurethane pads for absorption of shock and noise are available on each end of Series 2000-8000 Rotary Actuators. Reducing shock permits higher piston velocities for shorter cycle times. Reducing noise levels provides improved environment for increased productivity. Pads eliminate metal-to-metal contact between piston and end caps. **NOTE:** Air application only.



G SHAFT SEAL COVERS
Not available on Rx6x

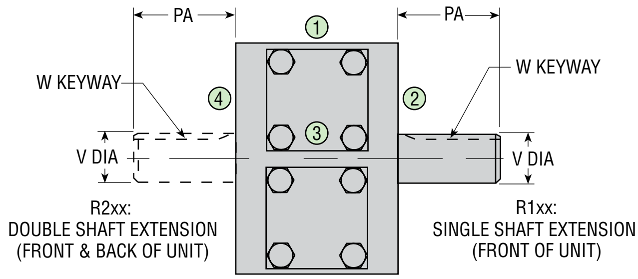
Fits all PHD Series 2000-8000, except when ordering hollow shafts. Isolates internal or external pressures. Maximum pressure differential is 500 psi [34.4 bar]. Furnished installed on actuator only (both sides). Covers are made of hard anodized aluminum. Not to be used as a pilot.



SERIES	LETTER A	LETTER B
2000	1.875 [47.63]	.688 [17.5]
4000	3.000 [76.20]	1.688 [42.9]
6000	3.250 [82.55]	1.688 [42.9]
8000	4.480 [113.79]	3.312 [84.1]

NUMBERS IN [ ] ARE FOR METRIC UNITS AND ARE IN mm.

BASIC SHAFT DIMENSIONS: R1xx and R2xx



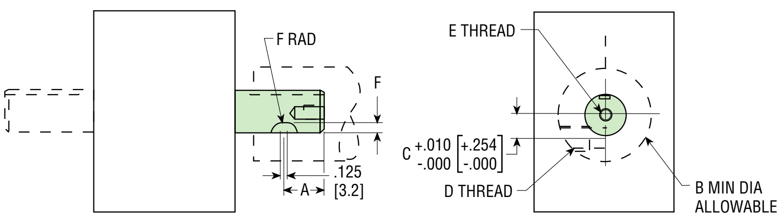
SERIES	LETTER DIMENSION				
	IMPERIAL*			METRIC**	
	PA	V	W	V	W
2000	.875	.4998/.5003	1/8 x 1/16 x .625	—	—
	[22]	[12.69/12.71]	[3.18 x 1.56 x 16]	[12.00/11.97]	[4 x 2.5 x 15]
4000	1.875	.8748/.8753	3/16 x 3/32 x 1.500	—	—
	[48]	[22.22/22.23]	[4.75 x 2.36 x 38]	[22.00/21.96]	[6 x 3.5 x 32]
6000	1.875	1.124/1.125	1/4 x 1/8 x 1.500	—	—
	[48]	[28.55/28.58]	[6.35 x 3.18 x 38]	[28.00/27.96]	[8 x 5 x 40]
8000	3.500	1.749/1.750	3/8 x 3/16 x 3.000	—	—
	[89]	[44.42/44.45]	[9.53 x 2.36 x 76]	[44.00/43.96]	[12 x 5 x 56]

NOTES:
1) **SHAFT KEYWAY:** SHOWN AT MID-ROTATION
2) *IMPERIAL SHAFT UNITS (Rx1x, Rx5x)
3) **METRIC SHAFT UNITS (Rx6x)

K PRELOADED KEYWAY SHAFT

Not available on Rx6x

Required when use of hub adaptor is desired.

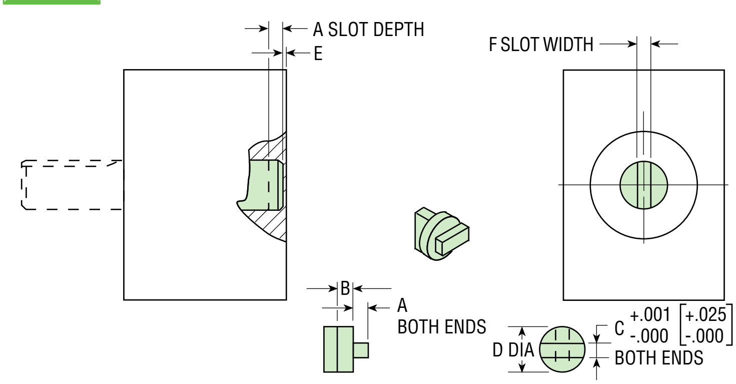


SHAFT KEYWAY: SHOWN AT MID-ROTATION
R2xx UNITS: WHEN ORDERING SPECIFY -K-K FOR PRELOAD ON BOTH SHAFT EXTENSIONS. PRELOAD WILL BE ON OPPOSITE SIDES OF SHAFT.
SET SCREW: INCLUDED WITH UNIT

SERIES	LETTER DIMENSION					
	A	B	C	D	E	F
2000	.375	1.500	.250	3/8-24	10-32 x .312 DP	.156
	[9.5]	[38.1]	[6.35]	[M10]	[M5 x 8]	[4]
4000	.812	2.000	.437	1/2-20	5/16-24 x .440 DP	.220
	[20.6]	[50.8]	[11.11]	[M12]	[M8 x 11]	[6]
6000	.812	3.000	.563	5/8-11	3/8-24 x .560 DP	.251
	[20.6]	[76.2]	[14.28]	[M16]	[M10 x 14]	[6]
8000	1.500	4.000	.875	1-8	1/2-20 x .687 DP	.438
	[38.1]	[101.6]	[22.22]	[M24]	[M12 x 17.5]	[11]

C CROSS KEY SHAFT

Not available on Rx6x

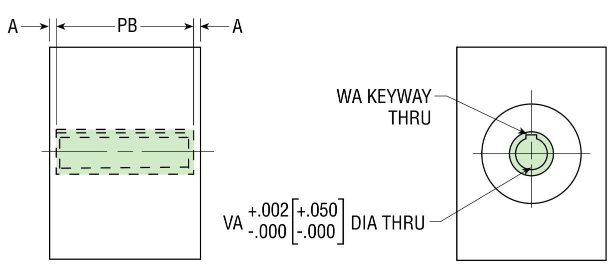


SERIES	LETTER DIMENSION					
	A	B	C	D	E	F
2000	.250	.215	.230	.500	.118	.250
	[6.4]	[5.5]	[5.8]	[12.7]	[3]	[6.3]
4000	.250	.265	.248	.875	.120	.248
	[6.4]	[6.7]	[6.3]	[22.2]	[3]	[6.3]
6000	.437	.485	.500	1.125	.150	.5002
	[11]	[12.3]	[12.7]	[28.6]	[3.8]	[12.7]
8000	.437	.805	.875	1.750	.245	.8752
	[11]	[20.4]	[22.2]	[44.5]	[6.2]	[22.2]

SHAFT KEYWAY: SHOWN AT MID-ROTATION
R2xx UNITS: WHEN ORDERING SPECIFY -C-C FOR CROSSKEY ON BOTH SHAFT EXTENSIONS
CROSSKEY: INCLUDED WITH UNIT

H HOLLOW SHAFT

Not available on Rx6x



SERIES	LETTER DIMENSION			
	A	PB	VA	WA
2000	.042	1.920	.250	—
	[1.1]	[48.76]	[6.35]	—
4000	.042	2.917	.500	1/8 x 1/16
	[1.1]	[74.09]	[12.7]	[3.18 x 1.58]
6000	.135	2.730	.687	3/16 x 3/32
	[3.4]	[69.34]	[17.46]	[4.76 x 2.38]
8000	.240	4.520	1.125	1/4 x 1/8
	[6.1]	[114.80]	[28.57]	[6.35 x 3.18]

SHAFT KEYWAY: SHOWN AT MID-ROTATION

MAGNETIC PISTON FOR USE WITH PHD PROXIMITY SWITCHES

See engineering page for Hydraulic Pressure Ratings with these options. See each ordering data for magnetic piston ordering information. Switches and brackets must be ordered separately. See Switches and Sensors section for complete switch information.

E SOLID STATE SWITCHES

Series 1000-8000 Rotary Actuators may be equipped with a magnetic band (specify -E) on the pistons which activates externally mounted PHD Solid State Switches. These switches allow the interfacing of the PHD Actuators to various logic systems. This option is for use with the following switches.

SERIES 1750 SOLID STATE SWITCHES

PART NO.	COLOR	DESCRIPTION
17503-2-06	Yellow	NPN (Sink) Type 4.5-24 VDC, 6 foot cable
17504-2-06	Red	PNP (Source) Type 4.5-24 VDC, 6 foot cable
17523-2	Yellow	NPN (Sink) Type 4.5-24 VDC, Quick Connect
17524-2	Red	PNP (Source) Type 4.5-24 VDC, Quick Connect

SWITCH BRACKETS

	PART NO.
SERIES	SERIES 1750
2000	17000-32-5
4000	17000-34-5
6000	17000-38-0
8000	17000-39-0

M REED SWITCHES

The PHD Magnetic Reed Switches may be used in situations where the Solid State Switches are not applicable. As with the Solid State Switches, a magnetic band (specify -M) on the pistons activates the externally mounted PHD Reed Switches. The Reed Switches may be used to signal a programmable controller, sequencer, relay, or in some cases, a valve solenoid. This option is for use with the following switches.

SERIES 1750 REED SWITCHES

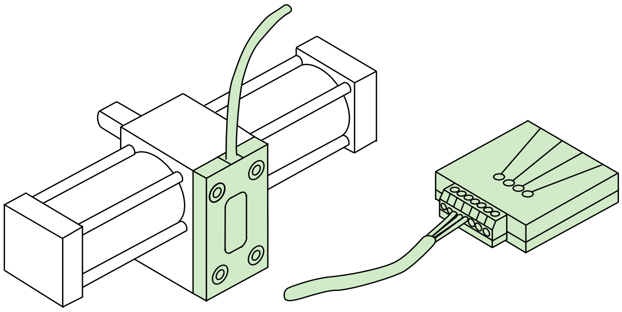
PART NO.	DESCRIPTION	
17502-2-06	White	NPN (Sink) or PNP (Source) 4.5-24 VDC, 6 foot cable
17509-3-06	Green	AC Type 110-120 VAC with Current Limit, 6 foot cable
17522-2	White	NPN (Sink) or PNP (Source) 4.5-24 VDC, Quick Connect
17529-3	Green	AC Type 110-120 VAC, Quick Connect with Current Limit

J SENSOR/SET POINT MODULE

Not available on Rx6x

PHD offers a solid state sensor transducer along with a Set Point Module which provides up to four adjustable sensing positions throughout the 180° maximum sensing range. These signals can be used as inputs to a programmable controller to signal ends of rotation in addition to multiple signals during rotation for indication of arc traveled.

The Set Point Module allows independent adjustment of each sensing position and is available for 4.5 to 24 VDC current sinking or current sourcing.



SET POINT MODULE

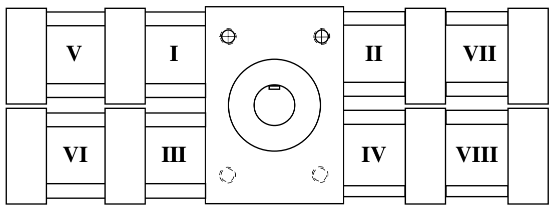
PART NO.	DESCRIPTION
9800-01-0300	NPN (Sink) 4.5-24 VDC
9800-01-0400	PNP (Source) 4.5-24 VDC

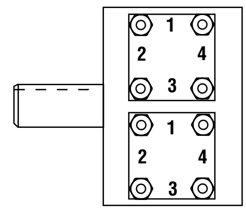
See Switches and Sensors section for information.

PORT & PORT CONTROL® LOCATIONS

Standard port location on all Multi-Position Actuators is position 2. Standard Port Control® and cushion adjustment needles are located in position 1 and 3. Other port and adjusting needle locations are available as specified.

Needles may not be located in same position as ports.





I — PORT POSITION 1 TOP RACK PORT POSITION 3 BOTTOM RACK

This option positions the ports in position 1 on tubes I, II, V, and VII and in position 3 on tubes III, IV, VI, and VIII. This allows access to the ports on the “Top” and “Bottom” sides of the actuator.

T — PORT POSITION 4

This option positions the ports in position 4 on all tubes.

V — FLUORO-ELASTOMER SEALS

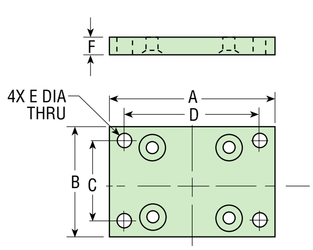
Fluoro-Elastomer seals are available to achieve seal compatibility with certain fluids. Seal compatibility should be checked with the fluid manufacturer for proper application.

Z1 — ELECTROLESS NICKEL PLATING

Electroless nickel plating is done on all externally exposed ferrous parts except the pinion shaft. This optional plating treatment gives an alternative method of protecting the unit from severe environments.

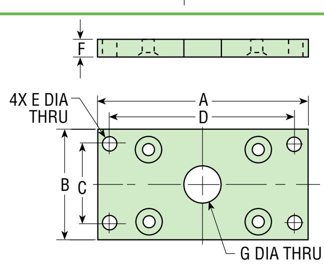
NOTE: Standard plating is Zinc and Black Oxide.

MOUNTING FLANGE (HARDWARE INCLUDED)



BOTTOM MOUNTING FLANGE

SERIES	KIT NO.		LETTER DIMENSION					
	IMPERIAL	METRIC	A	B	C	D	E	F
2000	13756	14320	4.250 [108]	2.000 [51]	1.625 [41.3]	2.625 [66.7]	.281 [7.1]	.250 [6.3]
4000	13757	14321	4.500 [114]	3.000 [76]	2.375 [60.3]	3.875 [98.4]	.406 [10.3]	.437 [11.1]
6000	13758	14322	4.500 [114]	4.000 [102]	3.375 [85.7]	3.875 [98.4]	.406 [10.3]	.437 [11.1]



SIDE MOUNTING FLANGE

SERIES	KIT NO.		LETTER DIMENSION						
	IMPERIAL	METRIC	A	B	C	D	E	F	G
2000	13759	14316	4.250 [108]	2.000 [51]	1.375 [34.9]	3.625 [92.1]	.281 [7.1]	.250 [6.3]	.625 [15.9]
4000	13760	14317	5.750 [146]	3.000 [76]	2.125 [54.0]	5.125 [130.2]	.406 [10.3]	.437 [11.1]	1.000 [25.4]
6000	13761	14318	6.500 [165]	4.000 [102]	3.375 [85.7]	5.875 [149.2]	.406 [10.3]	.437 [11.1]	1.250 [31.8]
8000	13762	14319	12.000 [305]	5.000 [127]	3.000 [76.2]	10.000 [254.0]	.781 [19.8]	.750 [19.1]	1.875 [47.6]

Low-Cost E Series Multifunction DAQ – 12 or 16-Bit, 200 kS/s, 16 Analog Inputs

NI E Series – Low-Cost

- 16 analog inputs at up to 200 kS/s, 12 or 16-bit resolution
- Up to 2 analog outputs at 10 kS/s, 12 or 16-bit resolution
- 8 digital I/O lines (TTL/CMOS); two 24-bit counter/timers
- Digital triggering
- 4 analog input signal ranges
- NI-DAQ driver that simplifies configuration and measurements

Families

- NI 6036E
- NI 6034E
- NI 6025E
- NI 6024E
- NI 6023E

Operating Systems

- Windows 2000/NT/XP
- Real-time performance with LabVIEW
- Others such as Linux® and Mac OS X

Recommended Software

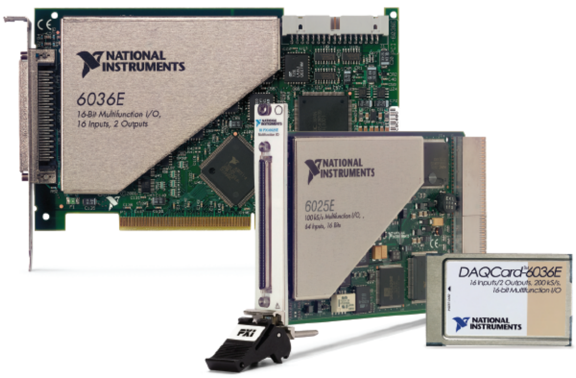
- LabVIEW
- LabWindows/CVI
- Measurement Studio
- VI Logger

Other Compatible Software

- Visual Basic, C/C++, and C#

Driver Software (included)

- NI-DAQ 7



Family	Bus	Analog Inputs	Input Resolution	Max Sampling Rate	Input Range	Analog Outputs	Output Resolution	Output Rate	Output Range	Digital I/O	Counter/Timers	Triggers
NI 6036E	PCI, PCMCIA	16 SE/8 DI	16 bits	200 kS/s	±0.05 to ±10 V	2	16 bits	10 kS/s[1]	±10 V	8	2, 24-bit	Digital
NI 6034E	PCI	16 SE/8 DI	16 bits	200 kS/s	±0.05 to ±10 V	0	–	–	–	8	2, 24-bit	Digital
NI 6025E	PCI, PXI	16 SE/8 DI	12 bits	200 kS/s	±0.05 to ±10 V	2	12 bits	10 kS/s[1]	±10 V	8	2, 24-bit	Digital
NI 6024E	PCI, PCMCIA	16 SE/8 DI	12 bits	200 kS/s	±0.05 to ±10 V	2	12 bits	10 kS/s[1]	±10 V	8	2, 24-bit	Digital
NI 6023E	PCI	16 SE/8 DI	12 bits	200 kS/s	±0.05 to ±10 V	0	–	–	–	8	2, 24-bit	Digital

[1] 10 kS/s typical when using the single DMA channel for analog output. 1 kS/s maximum when using the single DMA channel for either analog input or counter/timer operations. 1 kS/s maximum for PCMCIA DAQCard devices in all cases.

Table 1. Low-Cost E Series Model Guide

Overview and Applications

National Instruments low-cost E Series multifunction data acquisition devices provide full functionality at a price to meet the needs of the budget-conscious user. They are ideal for applications ranging from continuous high-speed data logging to control applications to high-voltage signal or sensor measurements when used with NI signal conditioning. Synchronize the operations of multiple devices using the RTSI bus or PXI trigger bus to easily integrate other hardware such as motion control and machine vision to create an entire measurement and control system.

Highly Accurate Hardware Design

NI low-cost E Series DAQ devices include the following features and technologies:

Temperature Drift Protection Circuitry – Designed with components that minimize the effect of temperature changes on measurements to less than 0.0010% of reading/°C.

Resolution-Improvement Technologies – Carefully designed noise floor maximizes the resolution.

Onboard Self-Calibration – Precise voltage reference included for calibration and measurement accuracy. Self-calibration is completely software controlled, with no potentiometers to adjust.

NI DAQ-STC – Timing and control ASIC designed to provide more flexibility, lower power consumption, and a higher immunity to noise and jitter than off-the-shelf counter/timer chips.

NI MITE – ASIC designed to optimize data transfer for multiple simultaneous operations using bus mastering with one DMA channel, interrupts, or programmed I/O.

NI PGIA – Measurement and instrument class amplifier that guarantees settling times at all gains. Typical commercial off-the-shelf amplifier components do not meet the settling time requirements for high-gain measurement applications.

PFI Lines – Eight programmable function input (PFI) lines that you can use for software-controlled routing of interboard and intraboard digital and timing signals.

RTSI or PXI Trigger Bus – Bus used to share timing and control signals between two or more PCI or PXI devices to synchronize operations.

RSE Mode – In addition to differential and nonreferenced single-ended modes, NI low-cost E Series devices offer the referenced single-ended (RSE) mode for use with floating-signal sources in applications with channel counts higher than eight.

Onboard Temperature Sensor – Included for monitoring the operating temperature of the device to ensure that it is operating within the specified range.

		Full-Featured E Series				Low-Cost E Series		Basic
Models		NI 6030E, NI 6031E, NI 6032E, NI 6033E	NI 6052E	NI 6070E, NI 6071E	NI 6040E	NI 6034E, NI 6036E	NI 6023E, NI 6024E, NI 6025E	PCI-6013, PCI-6014
Measurement Sensitivity[1] (mV)		0.0023	0.0025	0.009	0.008	0.0036	0.008	0.004
Nominal Range (V)								
Positive FS	**Negative FS**	**Absolute Accuracy (mV)**						
10	-10	1.147	4.747	14.369	15.373	7.560	16.504	8.984
5	-5	2.077	0.876	5.193	5.697	1.790	5.263	2.003
2.5	-2.5	–	1.190	3.605	3.859	–	–	–
2	-2	0.836	–	–	–	–	–	–
1	-1	0.422	0.479	1.452	1.556	–	–	–
0.5	-0.5	0.215	0.243	0.735	0.789	0.399	0.846	0.471
0.25	-0.25	–	0.137	0.379	0.405	–	–	–
0.2	-0.2	0.102	–	–	–	–	–	–
0.1	-0.1	0.061	0.064	0.163	0.176	–	–	–
0.05	-0.05	–	0.035	0.091	0.100	0.0611	0.106	0.069
10	0	0.976	1.232	6.765	7.269	–	–	–
5	0	1.992	2.119	5.391	5.645	–	–	–
2	0	0.802	0.850	2.167	2.271	–	–	–
1	0	0.405	0.428	1.092	1.146	–	–	–
0.5	0	0.207	0.242	0.558	0.583	–	–	–
0.2	0	0.098	0.111	0.235	0.247	–	–	–
0.1	0	0.059	0.059	0.127	0.135	–	–	–

Note: Accuracies are valid for measurements following an internal calibration. Measurement accuracies are listed for operational temperatures within ±1 °C of internal calibration temperature and ±10 °C of external or factory-calibration temperature. One-year calibration interval recommended. The Absolute Accuracy at Full Scale calculations were performed for a maximum range input voltage (for example, 10 V for the ±10 V range) after one year, assuming 100 pt averaging of data.

[1]Smallest detectable voltage change in the input signal at the smallest input range.

Table 2. E Series Analog Input Absolute Accuracy Specifications

		Full-Featured E Series				Low-Cost E Series		Basic
Models		NI 6030E, NI 6031E, NI 6032E, NI 6033E	NI 6052E	NI 6070E, NI 6071E	NI 6040E	NI 6034E, NI 6036E	NI 6023E, NI 6024E, NI 6025E	PCI-6013, PCI-6014
Nominal Range (V)								
Positive FS	**Negative FS**	**Absolute Accuracy (mV)**						
10	-10	1.430	1.405	8.127	8.127	2.417	8.127	3.835
10	0	1.201	1.176	5.685	5.685	–	–	–

Table 3. E Series Analog Output Absolute Accuracy Specifications

High-Performance, Easy-to-Use Driver Software

NI-DAQ is the robust driver software that makes it easy to access the functionality of your data acquisition hardware, whether you are a beginning or advanced user. Helpful features include:

Automatic Code Generation – DAQ Assistant is an interactive guide that steps you through configuring, testing, and programming measurement tasks and generates the necessary code automatically for NI LabVIEW, LabWindows/CVI, or Measurement Studio.

Cleaner Code Development – Basic and advanced software functions have been combined into one easy-to-use yet powerful set to help you build cleaner code and move from basic to advanced applications without replacing functions.

High-Performance Driver Engine – Software-timed single-point input (typically used in control loops) with NI-DAQ achieves rates of up to 50 kHz. NI-DAQ also delivers maximum I/O system throughput with a multithreaded driver.

Test Panels – With NI-DAQ, you can test all of your device functionality before you begin development.

Scaled Channels – Easily scale your voltage data into the proper engineering units using the NI-DAQ Measurement Ready virtual channels by choosing from a list of common sensors and signals or creating your own custom scale.

LabVIEW Integration – All NI-DAQ functions create the waveform data type, which carries acquired data and timing information directly into more than 400 LabVIEW built-in analysis routines for display of results in engineering units on a graph.

For information on applicable hardware for NI-DAQ 7, visit ni.com/dataacquisition.

Visit ni.com/oem for quantity discount information.

Recommended Accessories

Signal conditioning is required for sensor measurements or voltage inputs greater than 10 V. National Instruments SCXI is a versatile, high-performance signal conditioning platform, intended for high-channel-count applications. NI SCC products provide portable, flexible signal conditioning options on a per-channel basis. Both signal conditioning platforms are designed to increase the performance and reliability of your DAQ system, and are up to 10 times more accurate than terminal blocks (please visit **ni.com/sigcon** for more details). Refer to the table below for more information:

Sensor/Signals (>10 V)

System Description	DAQ Device	Signal Conditioning
High-performance	PCI-60xxE, PXI-60xxE, DAQCard-60xxE	SCXI
Low-cost, portable	PCI-60xxE, PXI-60xxE, DAQCard-60xxE	SCC

Signals (<10 V)[1]

System Description	DAQ Device	Terminal Block	Cable
Shielded	PCI-60xxE	SCB-68	SH6868-EP
Shielded	PXI-60xxE	TB-2705	SH6868-EP
Shielded	DAQCard-60xxE	SCB-68	SHC6868-EP
Low-cost	PCI-6025E/PXI-6025E	Two TBX-68s	SH1006868
Low-cost	PCI-60xxE/PXI-60xxE	CB-68LP	R6868
Low-cost	DAQCard-60xxE	CB-68LP	RC6868

[1]Terminal blocks do not provide signal conditioning (i.e., filtering, amplification, isolation, and so on), which may be necessary to increase the accuracy of your measurements.

Table 4. Recommended Accessories

Ordering Information

PCI

NI PCI-6036E........778465-01
NI PCI-6034E........778075-01
NI PCI-6025E........777744-01
NI PCI-6024E........777743-01
NI PCI-6023E........777742-01

PCMCIA

NI DAQCard-6036E........778561-01
NI DAQCard-6024E........778269-01

PXI

NI PXI-6025E........777798-01
Includes NI-DAQ driver software.

BUY NOW!

For complete product specifications, pricing, and accessory information, call (800) 813 3693 (U.S.) or go to **ni.com/dataacquisition**.

NI Services and Support

NI has the services and support to meet your needs around the globe and through the application life cycle – from planning and development through deployment and ongoing maintenance. We offer services and service levels to meet customer requirements in research, design, validation, and manufacturing. Visit **ni.com/services**.

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We also offer service programs that provide automatic upgrades to your application development environment and higher levels of technical support. Visit **ni.com/ssp**.

Hardware Services

NI Factory Installation Services

NI Factory Installation Services (FIS) is the fastest and easiest way to use your PXI or PXI/SCXI combination systems right out of the box. Trained NI technicians install the software and hardware and configure the system to your specifications. NI extends the standard warranty by one year on hardware components (controllers, chassis, modules) purchased with FIS. To use FIS, simply configure your system online with **ni.com/pxiadvisor**.

Calibration Services

NI recognizes the need to maintain properly calibrated devices for high-accuracy measurements. We provide manual calibration procedures, services to recalibrate your products, and automated calibration software specifically designed for use by metrology laboratories. Visit **ni.com/calibration**.

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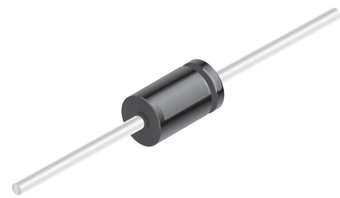
FAIRCHILD
SEMICONDUCTOR ™

1N4001 - 1N4007

Features

- Low forward voltage drop.
- High surge current capability.



DO-41
COLOR BAND DENOTES CATHODE

1.0 Ampere General Purpose Rectifiers

Absolute Maximum Ratings*
T_A = 25°C unless otherwise noted

Symbol	Parameter	Value	Units
$I_{F(AV)}$	Average Rectified Current .375 " lead length @ T_A = 75°C	1.0	A
I_{FSM}	Non-repetitive Peak Forward Surge Current 8.3 ms single half-sine-wave Superimposed on rated load (JEDEC method)	30	A
P_D	Total Device Dissipation Derate above 25°C	2.5 20	W mW/°C
$R_{\theta JA}$	Thermal Resistance, Junction to Ambient	50	°C/W
T_{stg}	Storage Temperature Range	-55 to +175	°C
T_J	Operating Junction Temperature	-55 to +150	°C

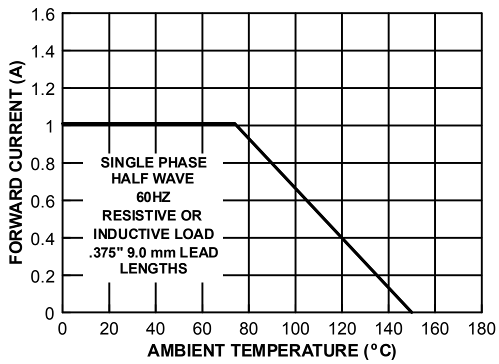
*These ratings are limiting values above which the serviceability of any semiconductor device may be impaired.

Electrical Characteristics
T_A = 25°C unless otherwise noted

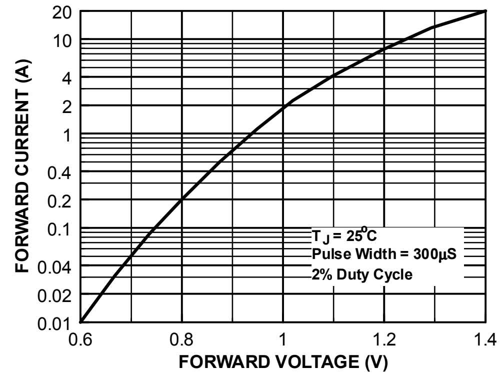
Symbol	Parameter	Device							Units
		4001	4002	4003	400	400	4006	4007	
V_{RRM}	Peak Repetitive Reverse Voltage	50	100	200	400	600	800	1000	V
V_{RMS}	Maximum RMS Voltage	35	70	140	280	420	560	700	V
V_R	DC Reverse Voltage (Rated V_R)	50	100	200	400	600	800	1000	V
I_{RM}	Maximum Instantaneous Reverse Current @ rated V_R T_A = 25°C T_A = 100°C	5.0 500							µA µA
V_{FM}	Maximum Instantaneous Forward Voltage @ 1.0 A	1.1							V
I_{rr}	Maximum Full Load Reverse Current, Full Cycle T_A = 75°C	30							µA
C	Typical Junction Capacitance V_R = 4.0 V, f = 1.0 MHz	15							pF

Typical Characteristics

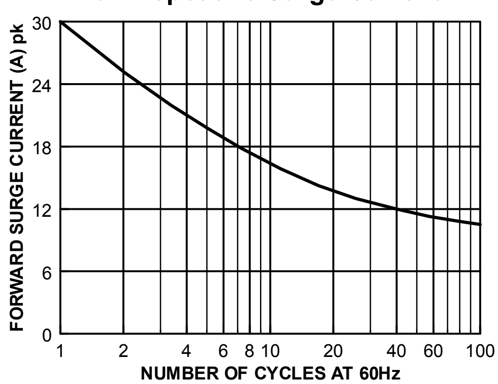
Forward Current Derating Curve



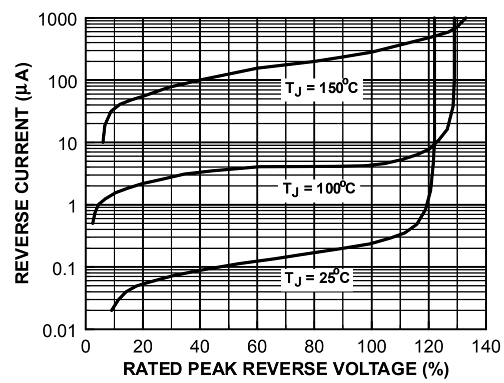
Forward Characteristics



Non-Repetitive Surge Current



Reverse Characteristics



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SuperSOT™-6
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As used herein:

1. Life support devices or systems are devices or systems which, (a) are intended for surgical implant into the body, or (b) support or sustain life, or (c) whose failure to perform when properly used in accordance with instructions for use provided in the labeling, can be reasonably expected to result in significant injury to the user.

2. A critical component is any component of a life support device or system whose failure to perform can be reasonably expected to cause the failure of the life support device or system, or to affect its safety or effectiveness.

PRODUCT STATUS DEFINITIONS

Definition of Terms

Datasheet Identification	Product Status	Definition
Advance Information	Formative or In Design	This datasheet contains the design specifications for product development. Specifications may change in any manner without notice.
Preliminary	First Production	This datasheet contains preliminary data, and supplementary data will be published at a later date. Fairchild Semiconductor reserves the right to make changes at any time without notice in order to improve design.
No Identification Needed	Full Production	This datasheet contains final specifications. Fairchild Semiconductor reserves the right to make changes at any time without notice in order to improve design.
Obsolete	Not In Production	This datasheet contains specifications on a product that has been discontinued by Fairchild semiconductor. The datasheet is printed for reference information only.

Rev. G

TOSHIBA Photocoupler GaAs Ired & Photo-Transistor

CNY17-2,CNY17-3,CNY17-4

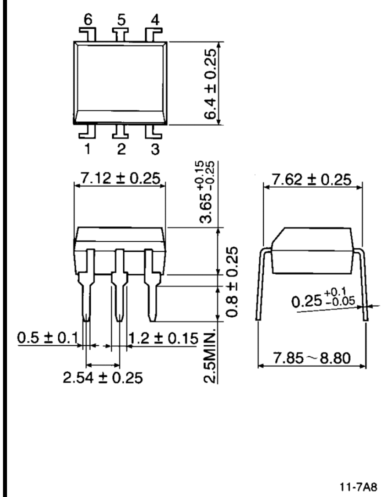
AC Line / Digital Logic Isolator

Digital Logic / Digital Logic Isolator
Telephone Line Receiver
Twisted Pair Line Receiver
High Frequency Power Supply Feedback Control
Relay Contact Monitor

The TOSHIBA Corporation CNY17 consist of a gallium arsenide infrared emitting diode coupled with a silicon photo transistor in a dual in−line package.

- Small package size and low cost
- Fast switching speeds: 5μs (typ.)
- High DC current transfer ratio: CTR(I_F = 10mA, V_{CE} = 5V)
  - CNY17−2: 63~125%
  - CNY17−3: 100~200%
  - CNY17−4: 160~320%
- High isolation resistance: $10^{11}\Omega$ (typ.)
- High isolation voltage: 4400V (min.)

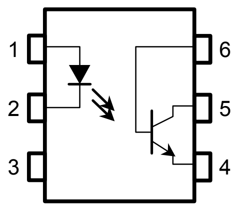
Unit in mm



TOSHIBA 11−7A8

Weight: 0.4 g

Pin Configuration



1 : Anode
2 : Cathode
3 : N.C.
4 : Emitter
5 : Collector
6 : Base

Maximum Ratings (Ta = 25°C)

	Characteristic	Symbol	Rating	Unit
LED	Forward current	I_F	60	mA
	Forward current derating	ΔI_F / °C	0.8 *	mA / °C
	Peak forward current (Note)	I_{PF}	3	A
	Power dissipation	P_D	100	mW
	Power dissipation derating	ΔP_D / °C	1.33 *	mW / °C
	Reverse voltage	V_R	6	V
Photo−transistor	Collector−emitter voltage	BV_{CEO}	70	V
	Collector−base voltage	BV_{CBO}	70	V
	Emitter−collector voltage	BV_{ECO}	7	V
	Collector current	I_C	100	mA
	Power dissipation	P_C	150	mW
	Power dissipation derating	ΔP_C / °C	2.0 *	mW / °C
Coupled	Storage temperature	T_{stg}	−55~150	°C
	Operating temperature	T_{opr}	−55~100	°C
	Lead soldering temperature (10 s)	T_{sol}	260	°C
	Total package dissipation	P_T	200	mW
	Total package power dissipation derating	ΔP_T / °C	2.6 *	mW / °C

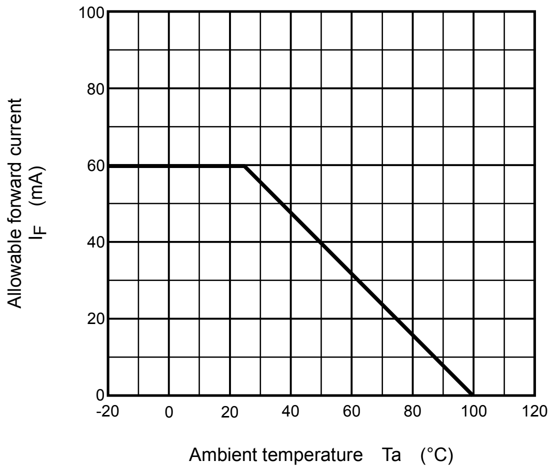
(Note)Pulse width 1μs, 300pps.

* Above 25°C ambient.

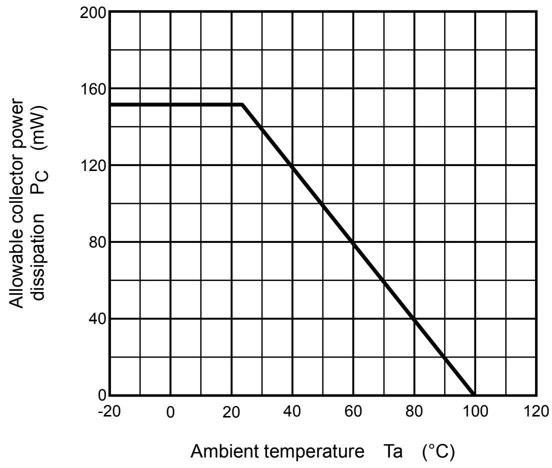
Electrical Characteristics (Ta = 25°C)

	Characteristic		Symbol	Test Condition	Min.	Typ.	Max.	Unit
LED	Forward voltage		V_F	I_F = 60 mA	—	1.35	1.65	V
LED	Reverse current		I_R	V_R = 3 V	—	—	10	μA
LED	Capacitance		C_D	V = 0, f = 1 MHz	—	30	—	pF
Photo−transistor	DC forward current gain		h_{FE}	V_{CE} = 5, I_C = 500 μA	100	200	—	
Photo−transistor	Collector−emitter breakdown voltage		$V_{(BR)\ CEO}$	I_C = 1 mA, I_F = 0	70	—	—	V
Photo−transistor	Collector−base breakdown voltage		$V_{(BR)\ CBO}$	I_C = 100 μA, I_F = 0	70	—	—	V
Photo−transistor	Emitter−collector breakdown voltage		$V_{(BR)\ ECO}$	I_E = 100 μA, I_F = 0	7	—	—	V
Photo−transistor	Collector dark current		I_{CEO}	V_{CE} = 10 V, I_F = 0	—	1	50	nA
Photo−transistor	Collector dark current		I_{CBO}	V_{CB} = 10 V, I_F = 0	—	0.1	20	nA
Photo−transistor	Collector−emitter capacitance		C_{CE}	V = 0, f = 1 MHz	—	10	—	pF
Coupled	Current transfer ratio	CNY17−2	CTR	I_F = 10 mA, V_{CE} = 5 V	63	—	125	%
		CNY17−3			100	—	200	
		CNY17−4			160	—	320	
Coupled	Saturation voltage		$V_{CE\ (sat)}$	I_F = 10 mA, I_C = 2.5 mA	—	—	0.4	V
Coupled	Capacitance input to output		C_S	V = 0, f = 1 MHz	—	0.8	—	pF
Coupled	Isolation resistance		R_S	V = 500 V	—	10^{11}	—	Ω
Coupled	DC isolation voltage		BV_S	DC 1 minute	4400	—	—	V
Coupled	Rise fall time		t_r / t_f	V_{CE} = 10 V, I_C = 2 mA R_L = 100 Ω	—	5	10	μs
Coupled	Rise / fall time photo diode		t_r / t_f	V_{CB} = 10 V, I_{CB} = 50 μA R_L = 100Ω	—	200	—	ns

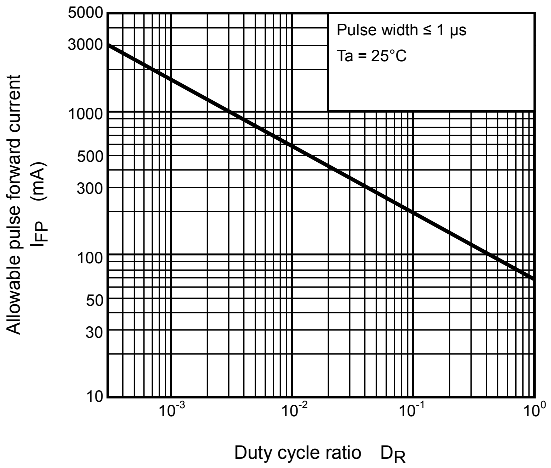
I_F – Ta



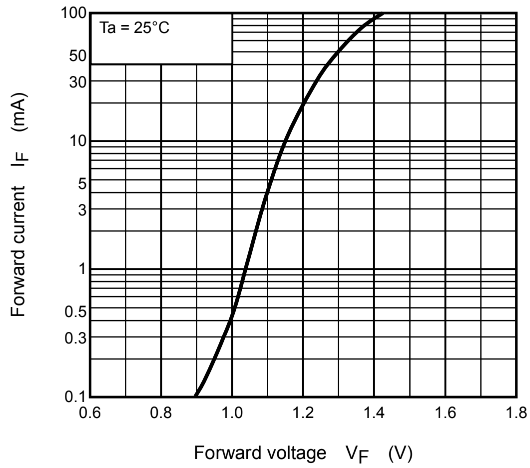
P_C – Ta



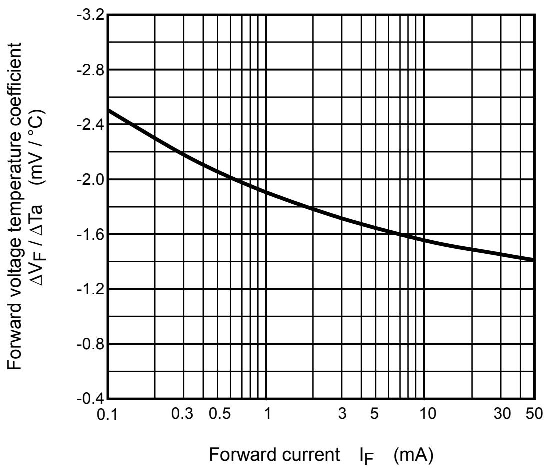
I_{FP} – D_R



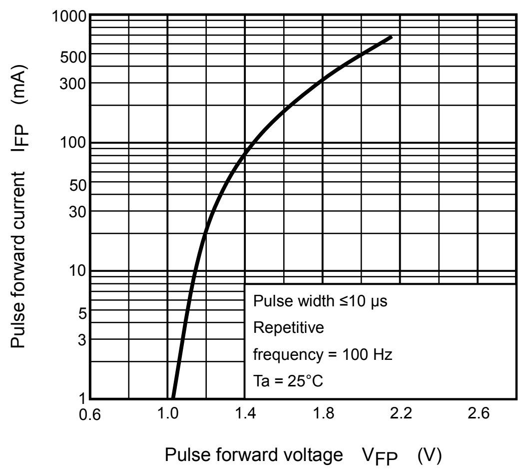
I_F – V_F



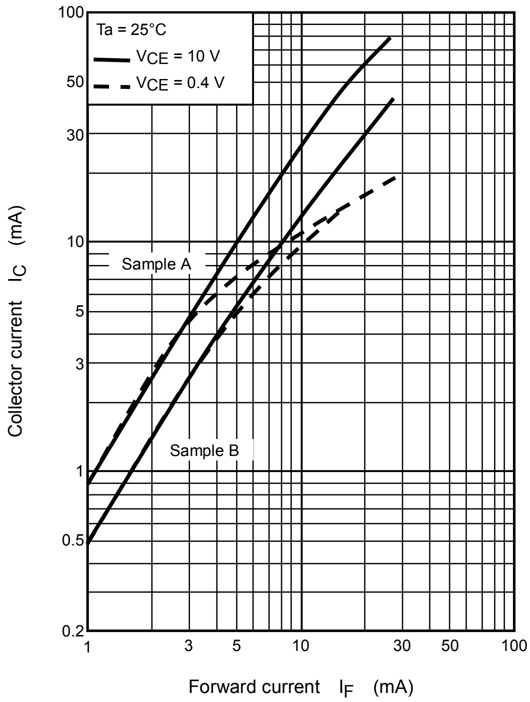
ΔV_F / ΔTa – I_F



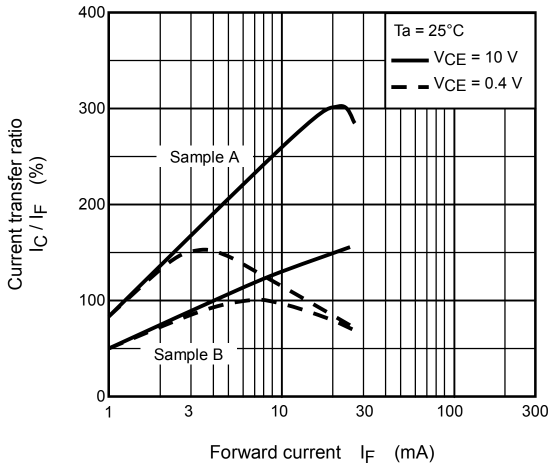
I_{FP} – V_{FP}



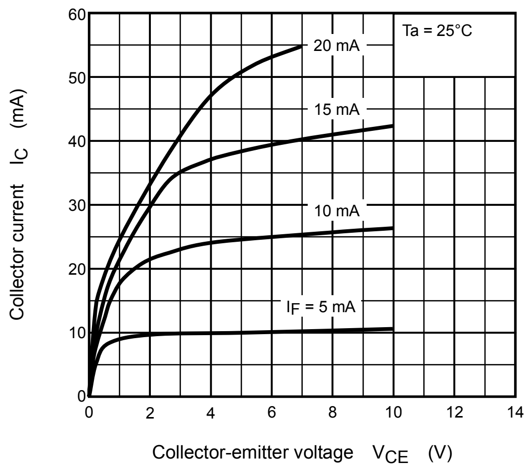
I_C / I_F



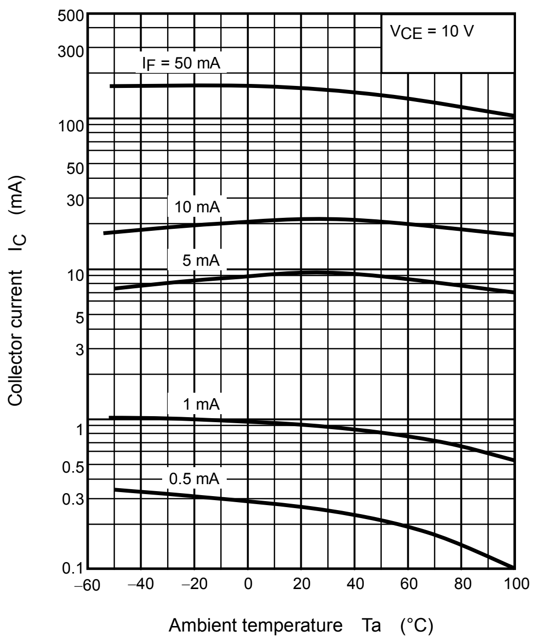
I_C / I_F – I_F



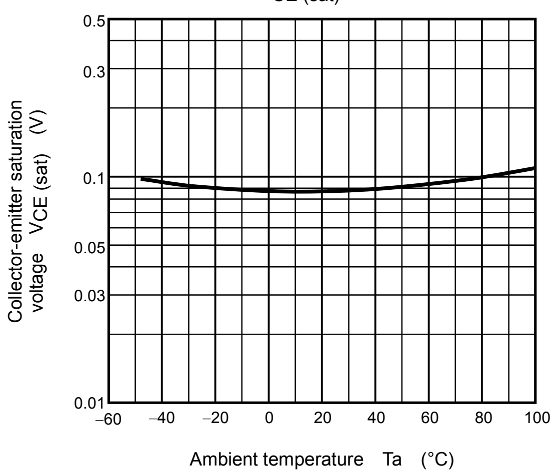
I_C – V_{CE}



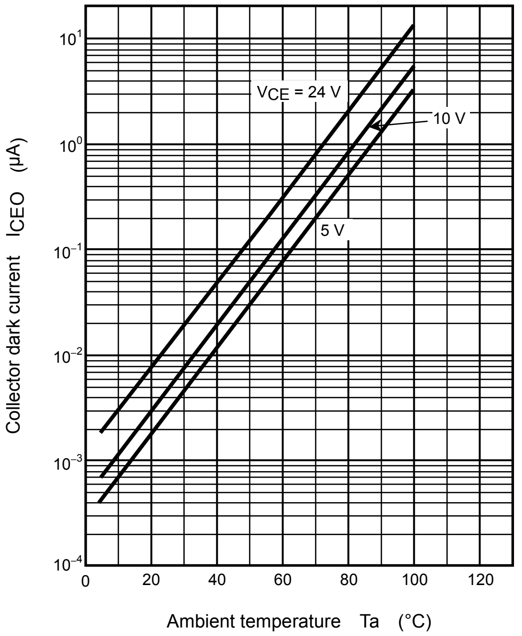
I_C – Ta



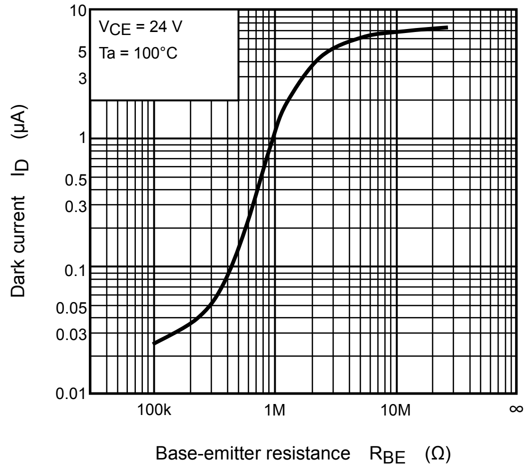
$V_{CE\ (sat)}$ – Ta



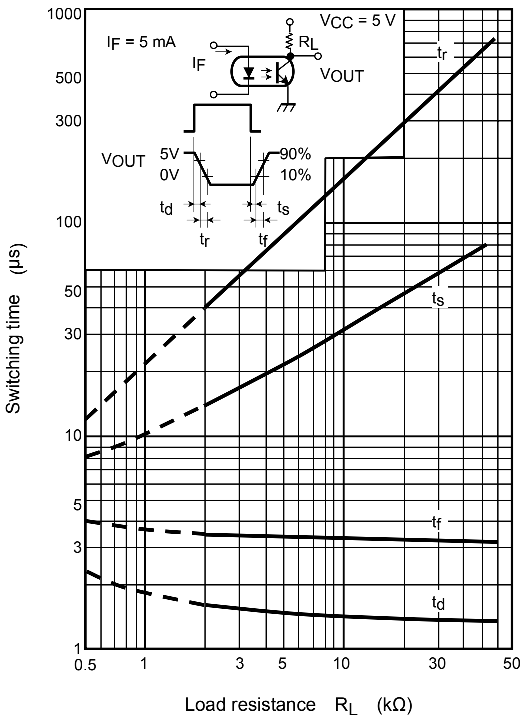
I_{CEO} – Ta



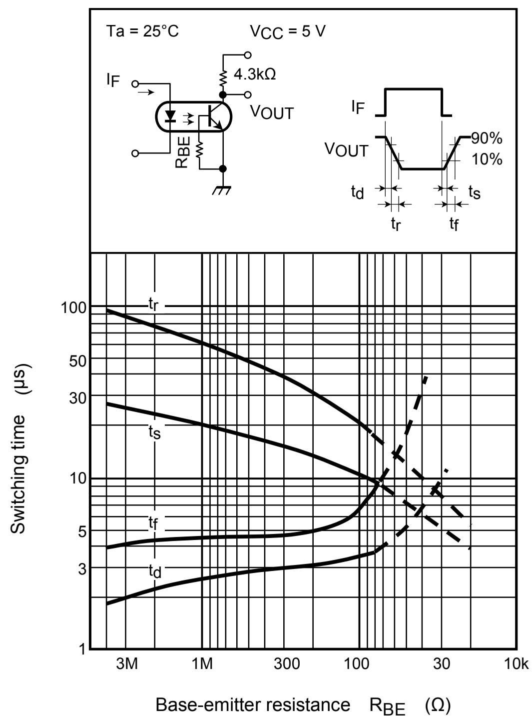
I_D – R_{BE}



Switching Characteristics – R_L
(Saturated Operation)



R_{BE} – Switching Characteristics
(Saturated Operation)



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000707EBC

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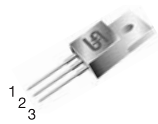
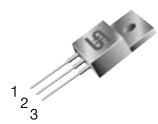
TS7800

3-Terminal Fixed Positive Voltage Regulators

TO-220



ITO-220



Pin: 1. Input 2. Ground 3. Output
(Heatsink surface connected to Pin 2.)

Voltage Range
5 to 24 Volts
Current
1 Ampere

Features

- ✧ Output Current up to 1 Ampere
- ✧ No External Components Required
- ✧ Internal Thermal Overload Protection
- ✧ Internal Short-Circuit Current Limiting
- ✧ Output Transistor Safe-Area Compensation
- ✧ Output Voltage Offered in 4% Tolerance

Ordering Informations

Device	Operating Temperature (Ambient)	Package
TS78xxCZ	-20°C to +85°C	TO-220
TS78xxCI		TO-220F

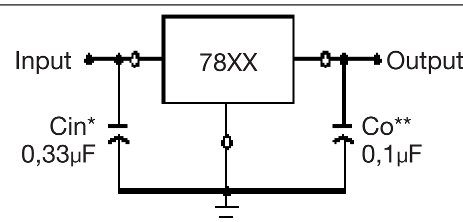
Absolute Maximum Ratings (Ta=25°C)

Ratings		Symbol	TS7800 Series	Unit
Input Voltage		Vin *	35	V
Input Voltage		Vin **	40	V
Power Dissipation	TO-220	Without heatsink	2	°C/W
	TO-220	Pt ***	15	
	TO-220F	With heatsink	10	
Operating Ambient Temperature		Topr	-20 to +85	°C
Operating Junction Temperature		Tj	0 to +125	°C
Storage Temperature		Tstg	-25 to +150	°C

Note: * TS7805 to TS7818 ** TS7824 *** Follow the derating curve

Standard Application

A common ground is required between the input and the output voltages. The input voltage must remain typically 2.0V above the output voltage even during the low point on the Input ripple voltage.



XX = these two digits of the type number indicate voltage.

* = Cin is required if regulator is located an appreciable distance from power supply filter.

** = Co is not needed for stability; however, it does improve transient response.

Rev. 1 03/2003

TS7805 Electrical Characteristics

(Vin=10V, Iout=500mA, 0°C Tj 125°C, Cin=0.33µF, Cout=0.1µF; unless otherwise specified.)

Characteristics	Symbol	Test Conditions	Min.	Typ.	Max.	Unit
Output Voltage	Vout	Tj=25°C	4.80	5	5.20	V
		7V Vin 20V, 5mA Iout 1.5A, PD 15W	4.75	5	5.25	V
Line Regulation	REGline	Tj=25°C 7.5V Vin 25V	--	3	100	mV
		8V Vin 12V	--	1	50	mV
Load Regulation	REGload	Tj=25°C 5mA Iout 1.5A	--	15	100	mV
		250mA Iout 750mA	--	5	50	mV
Quiescent Current	Iq	Iout=0, Tj=25°C	--	4.2	8	mA
Quiescent Current Change	Iq	7V Vin 25V	--	--	1.3	mA
		5mA Iout 1.5A	--	--	0.5	mA
Output Noise Voltage	Vn	10Hz f 100KHz, Tj=25°C	--	40	--	µV
Ripple Rejection Ratio	RR	f=120Hz, 8V Vin 18V	62	78	--	dB
Voltage Drop	Vdrop	Iout=1.0A, Tj=25°C	--	2	--	V
Output Resistance	Rout	f=1KHz	--	17	--	m
Output Short Circuit Current	Ios	Tj=25°C	--	750	--	mA
Peak Output Current	Io peak	Tj=25°C	--	2.2	--	A
Temperature Coefficient Output Voltage	Vout/ Tj	Iout=5mA, 0°C Tj 125°C	--	-0.6	--	mV/°C

TS7806 Electrical Characteristics

(Vin=11V, Iout=500mA, 0°C Tj 125°C, Cin=0.33µF, Cout=0.1µF; unless otherwise specified.)

Characteristics	Symbol	Test Conditions	Min.	Typ.	Max.	Unit
Output Voltage	Vout	Tj=25°C	5.75	6	6.25	V
		8V Vin 21V, 5mA Iout 1.5A, PD 15W	6.3	6	6.3	V
Line Regulation	REGline	Tj=25°C 8V Vin 25V	--	5	120	mV
		9V Vin 13V	--	1.5	60	mV
Load Regulation	REGload	Tj=25°C 5mA Iout 1.5A	--	14	120	mV
		250mA Iout 750mA	--	4	60	mV
Quiescent Current	Iq	Iout=0, Tj=25°C	--	4.3	8	mA
Quiescent Current Change	Iq	8V Vin 25V	--	--	1.3	mA
		5mA Iout 1.5A	--	--	0.5	mA
Output Noise Voltage	Vn	10Hz f 100KHz, Tj=25°C	--	45	--	µV
Ripple Rejection Ratio	RR	f=120Hz, 9V Vin 19V	59	75	--	dB
Voltage Drop	Vdrop	Iout=1.0A, Tj=25°C	--	2	--	V
Output Resistance	Rout	f=1KHz	--	19	--	m
Output Short Circuit Current	Ios	Tj=25°C	--	550	--	mA
Peak Output Current	Io peak	Tj=25°C	--	2.2	--	A
Temperature Coefficient of Output Voltage	Vout/ Tj	Iout=5mA, 0°C Tj 125°C	--	-0.7	--	mV/°C

Pulse testing techniques are used to maintain the junction temperature as close to the ambient temperature as possible, and thermal effects must be taken into account separately. This specification applies only for DC power dissipation permitted by absolute maximum ratings.

Rev. 1   03/2003

TS7808 Electrical Characteristics

(Vin=14V, Iout=500mA, 0°C Tj 125°C, Cin=0.33µF, Cout=0.1µF; unless otherwise specified.)

Characteristics	Symbol	Test Conditions	Min.	Typ.	Max.	Unit
Output Voltage	Vout	Tj=25°C	7.69	8	8.32	V
		10.5V Vin 23V, 5mA Iout 1.5A, PD 15W	7.61	8	8.40	V
Line Regulation	REGline	Tj=25°C 10.5V Vin 25V	--	6	160	mV
		Tj=25°C 11V Vin 17V	--	2	80	mV
Load Regulation	REGload	Tj=25°C 10mA Iout 1.5A	--	12	160	mV
		Tj=25°C 250mA Iout 750mA	--	4	80	mV
Quiescent Current	Iq	Iout=0, Tj=25°C	--	4.3	8	mA
Quiescent Current Change	Iq	10.5V Vin 25V	--	--	1	mA
		5mA Iout 1.5A	--	--	0.5	mA
Output Noise Voltage	Vn	10Hz f 100KHz, Tj=25°C	--	52	--	µV
Ripple Rejection Ratio	RR	f=120Hz, 11V Vin 21V	56	72	--	dB
Voltage Drop	Vdrop	Iout=1.0A, Tj=25°C	--	2	--	V
Output Resistance	Rout	f=1KHz	--	16	--	m
Output Short Circuit Current	Ios	Tj=25°C	--	450	--	mA
Peak Output Current	Io peak	Tj=25°C	--	2.2	--	A
Temperature Coefficient of Output Voltage	Vout/ Tj	Iout=5mA, 0°C Tj 125°C	--	-0.8	--	mV/°C

TS7809 Electrical Characteristics

(Vin=15V, Iout=500mA, 0°C Tj 125°C, Cin=0.33µF, Cout=0.1µF; unless otherwise specified.)

Characteristics	Symbol	Test Conditions	Min.	Typ.	Max.	Unit
Output Voltage	Vout	Tj=25°C	8.65	9	9.36	V
		11.5V Vin 24V, 5mA Iout 1.5A, PD 15W	8.57	9	9.45	V
Line Regulation	REGline	Tj=25°C 11.5V Vin 26V	--	6	180	mV
		Tj=25°C 11.5V Vin 17V	--	2	90	mV
Load Regulation	REGload	Tj=25°C 5mA Iout 1.5A	--	12	180	mV
		Tj=25°C 250mA Iout 750mA	--	4	90	mV
Quiescent Current	Iq	Iout=0, Tj=25°C	--	4.3	8	mA
Quiescent Current Change	Iq	11.5V Vin 26V	--	--	1	mA
		5mA Iout 1.5A	--	--	0.5	mA
Output Noise Voltage	Vn	10Hz f 100KHz, Tj=25°C	--	52	--	µV
Ripple Rejection Ratio	RR	f=120Hz, 11.5V Vin 21.5V	55	72	--	dB
Voltage Drop	Vdrop	Iout=1.0A, Tj=25°C	--	2	--	V
Output Resistance	Rout	f=1KHz	--	16	--	m
Output Short Circuit Current	Ios	Tj=25°C	--	450	--	mA
Peak Output Current	Io peak	Tj=25°C	--	2.2	--	A
Temperature Coefficient of Output Voltage	Vout/ Tj	Iout=5mA, 0°C Tj 125°C	--	-1	--	mV/°C

Pulse testing techniques are used to maintain the junction temperature as close to the ambient temperature as possible, and thermal effects must be taken into account separately. This specification applies only for DC power dissipation permitted by absolute maximum ratings.

TS7810 Electrical Characteristics

(Vin=16V, Iout=500mA, 0°C Tj 125°C, Cin=0.33μF, Cout=0.1μF; unless otherwise specified.)

Characteristics	Symbol	Test Conditions		Min.	Typ.	Max.	Unit
Output Voltage	Vout	Tj=25°C		9.6	10	10.4	V
		12.5V Vin 25V, 5mA Iout 1.5A, PD 15W		9.5	10	10.5	V
Line Regulation	REGline	Tj=25°C	12.5V Vin 28V	--	7	200	mV
			13V Vin 17V	--	2	100	mV
Load Regulation	REGload	Tj=25°C	10mA Iout 1.5A	--	12	200	mV
			250mA Iout 750mA	--	4	100	mV
Quiescent Current	Iq	Iout=0, Tj=25°C		--	4.3	8	mA
Quiescent Current Change	Iq	12.5V Vin 28V		--	--	1	mA
		5mA Iout 1.5A		--	--	0.5	mA
Output Noise Voltage	Vn	10Hz f 100KHz, Tj=25°C		--	70	--	μV
Ripple Rejection Ratio	RR	f=120Hz, 13V Vin 23V		55	71	--	dB
Voltage Drop	Vdrop	Iout=1.0A, Tj=25°C		--	2	--	V
Output Resistance	Rout	f=1KHz		--	18	--	m
Output Short Circuit Current	Ios	Tj=25°C		--	400	--	mA
Peak Output Current	Io peak	Tj=25°C		--	2.2	--	A
Temperature Coefficient of Output Voltage	Vout/ Tj	Iout=5mA, 0°C Tj 125°C		--	-1	--	mV/°C

TS7812 Electrical Characteristics

(Vin=19V, Iout=500mA, 0°C Tj 125°C, Cin=0.33μF, Cout=0.1μF; unless otherwise specified.)

Characteristics	Symbol	Test Conditions		Min.	Typ.	Max.	Unit
Output Voltage	Vout	Tj=25°C		11.53	12	12.48	V
		14.5V Vin 27V, 5mA Iout 1.5A, PD 15W		11.42	12	12.60	V
Line Regulation	REGline	Tj=25°C	14V Vin 30V	--	10	240	mV
			15V Vin 19V	--	3	120	mV
Load Regulation	REGload	Tj=25°C	10mA Iout 1.5A	--	12	240	mV
			250mA Iout 750mA	--	4	120	mV
Quiescent Current	Iq	Tj=25°C, Iout=0		--	4.3	8	mA
Quiescent Current Change	Iq	14.5V Vin 30V		--	--	1	mA
		5mA Iout 1.5A		--	--	0.5	mA
Output Noise Voltage	Vn	10Hz f 100KHz, Tj=25°C		--	75	--	μV
Ripple Rejection Ratio	RR	f=120Hz, 15V Vin 25V		55	71	--	dB
Voltage Drop	Vdrop	Iout=1.0A, Tj=25°C		--	20	--	V
Output Resistance	Rout	f=1KHz		--	18	--	m
Output Short Circuit Current	Ios	Tj=25°C		--	350	--	mA
Peak Output Current	Io peak	Tj=25°C		--	2.2	--	A
Temperature Coefficient of Output Voltage	Vout/ Tj	Iout=5mA, 0°C Tj 125°C		--	-1	--	mV/°C

Pulse testing techniques are used to maintain the junction temperature as close to the ambient temperature as possible, and thermal effects must be taken into account separately. This specification applies only for DC power dissipation permitted by absolute maximum ratings.

TS7815 Electrical Characteristics

(Vin=23V, Iout=500mA, 0°C Tj 125°C, Cin=0.33µF, Cout=0.1µF; unless otherwise specified.)

Characteristics	Symbol	Test Conditions		Min.	Typ.	Max.	Unit
Output Voltage	Vout	Tj=25°C		14.42	15	15.60	V
		17.5V Vin 30V, 5mA Iout 1.5A, PD 15W		14.28	15	15.75	V
Line Regulation	REGline	Tj=25°C	17.5V Vin 30V	--	12	300	mV
			18V Vin 22V	--	3	150	mV
Load Regulation	REGload	Tj=25°C	10mA Iout 1.5A	--	12	300	mV
			250mA Iout 750mA	--	4	150	mV
Quiescent Current	Iq	Tj=25°C, Iout=0		--	4.3	8	mA
Quiescent Current Change	Iq	17.5V Vin 30V		--	--	1	mA
		5mA Iout 1.5A		--	--	0.5	mA
Output Noise Voltage	Vn	10Hz f 100KHz, Tj=25°C		--	90	--	µV
Ripple Rejection Ratio	RR	f=120Hz, 18V Vin 28V		54	70	--	dB
Voltage Drop	Vdrop	Iout=1.0A, Tj=25°C		--	2	--	V
Output Resistance	Rout	f=1KHz		--	19	--	m
Output Short Circuit Current	Ios	Tj=25°C		--	230	--	mA
Peak Output Current	Io peak	Tj=25°C		--	2.1	--	A
Temperature Coefficient of Output Voltage	Vout/ Tj	Iout=5mA, 0°C Tj 125°C		--	-1	--	mV/°C

TS7818 Electrical Characteristics

(Vin=27V, Iout=500mA, 0°C Tj 125°C, Cin=0.33µF, Cout=0.1µF; unless otherwise specified.)

Characteristics	Symbol	Test Conditions		Min.	Typ.	Max.	Unit
Output Voltage	Vout	Tj=25°C		17.30	18	18.72	V
		21V Vin 33V, 5mA Iout 1.5A, PD 15W		17.14	18	18.90	V
Line Regulation	REGline	Tj=25°C	21V Vin 33V	--	15	360	mV
			22V Vin 26V	--	5	180	mV
Load Regulation	REGload	Tj=25°C	10mA Iout 1.5A	--	12	360	mV
			250mA Iout 750mA	--	4	180	mV
Quiescent Current	Iq	Tj=25°C, Iout=0		--	4.5	8	mA
Quiescent Current Change	Iq	21V Vin 33V		--	--	1	mA
		5mA Iout 1.5A		--	--	0.5	mA
Output Noise Voltage	Vn	10Hz f 100KHz, Tj=25°C		--	110	--	µV
Ripple Rejection Ratio	RR	f=120Hz, 21V Vin 31V		54	70	--	dB
Voltage Drop	Vdrop	Iout=1.0A, Tj=25°C		--	2	--	V
Output Resistance	Rout	f=1KHz		--	22	--	m
Output Short Circuit Current	Ios	Tj=25°C		--	200	--	mA
Peak Output Current	Io peak	Tj=25°C		--	2.1	--	A
Temperature Coefficient of Output Voltage	Vout/ Tj	Iout=5mA, 0°C Tj 125°C		--	-1	--	mV/°C

Pulse testing techniques are used to maintain the junction temperature as close to the ambient temperature as possible, and thermal effects must be taken into account separately. This specification applies only for DC power dissipation permitted by absolute maximum ratings.

TS7824 Electrical Characteristics

(Vin=33V, Iout=500mA, 0°C Tj 125°C, Cin=0.33µF, Cout=0.1µF; unless otherwise specified.)

Characteristics	Symbol	Test Conditions		Min.	Typ.	Max.	Unit
Output Voltage	Vout	Tj=25°C		23.07	24	24.96	V
		26V Vin 38V, 5mA Iout 1.5A, PD 15W		22.85	24	25.20	V
Line Regulation	REGline	Tj=25°C	26V Vin 38V	--	18	480	mV
			27V Vin 32V	--	6	240	mV
Load Regulation	REGload	Tj=25°C	10mA Iout 1.5A	--	12	480	mV
			250mA Iout 750mA	--	4	240	mV
Quiescent Current	Iq	Iout=0, Tj=25°C		--	4.6	8	mA
Quiescent Current Change	Iq	26V Vin 38V		--	--	1	mA
		5mA Iout 1.5A		--	--	0.5	mA
Output Noise Voltage	Vn	10Hz f 100KHz, Tj=25°C		--	170	--	µV
Ripple Rejection Ratio	RR	f=120Hz, 26V Vin 36V		54	70	--	dB
Voltage Drop	Vdrop	Iout=1.0A, Tj=25°C		--	2	--	V
Output Resistance	Rout	f=1KHz		--	28	--	m
Output Short Circuit Current	Ios	Tj=25°C		--	150	--	mA
Peak Output Current	Io peak	Tj=25°C		--	2.1	--	A
Temperature Coefficient of Output Voltage	Vout/ Tj	Iout=5mA, 0°C Tj 125°C		--	-1.5	--	mV/°C

Pulse testing techniques are used to maintain the junction temperature as close to the ambient temperature as possible, and thermal effects must be taken into account separately.
This specification applies only for DC power dissipation permitted by absolute maximum ratings.

FIG. 1 - WORST CASE POWER DISSIPATION versus AMBIENT TEMPERATURE

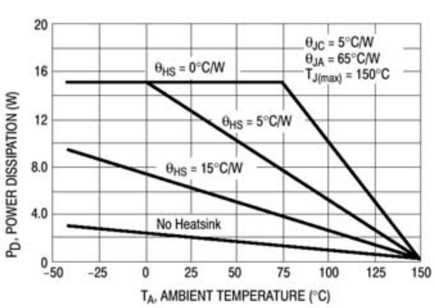


FIG. 2 - PEAK OUTPUT CURRENT AS A FUNCTION OF INPUT-OUTPUT DIFFERENTIAL VOLTAGE

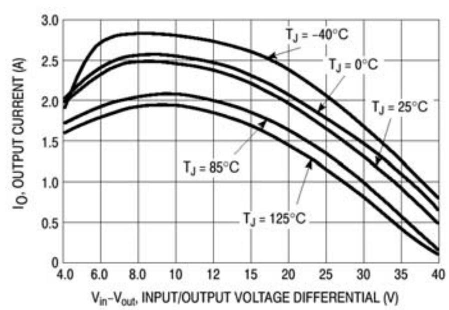


FIG. 3 - QUIESCENT CURRENT AS A FUNCTION OF TEMPERATURE

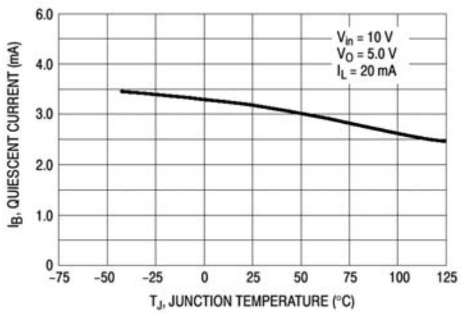


FIG. 4 - INPUT OUTPUT DIFFERENTIAL AS A FUNCTION OF JUNCTION TEMPERATURE

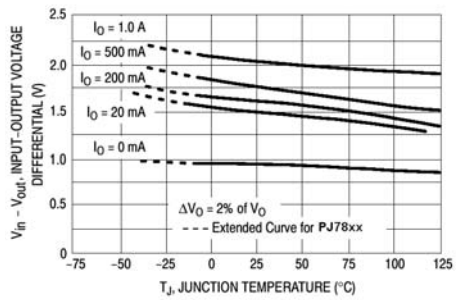


FIG. 5 - OUTPUT VOLTAGE AS A FUNCTION OF JUNCTION TEMPERATURE

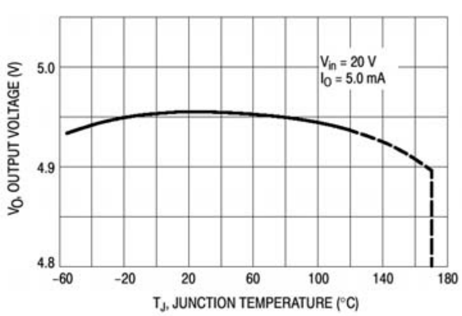


FIG. 6 - OUTPUT IMPEDANCE AS A FUNCTION OF OUTPUT VOLTAGE

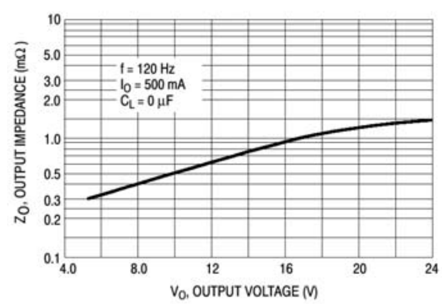


FIG. 7 - RIPPLE REJECTION AS A FUNCTION OF OUTPUT VOLTAGE

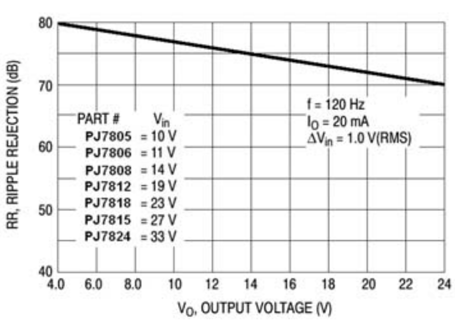
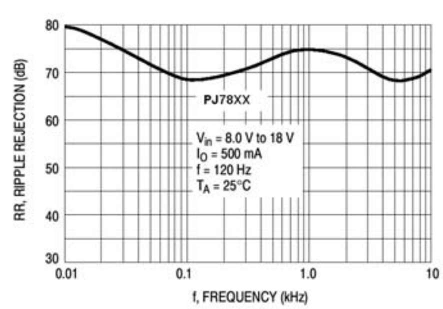


FIG. 8 - RIPPLE REJECTION AS A FUNCTION OF FREQUENCY



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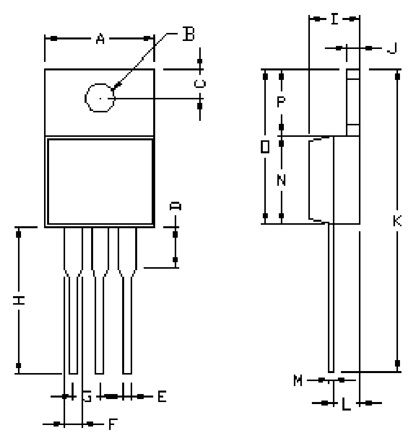
TO-220 Mechanical drawing

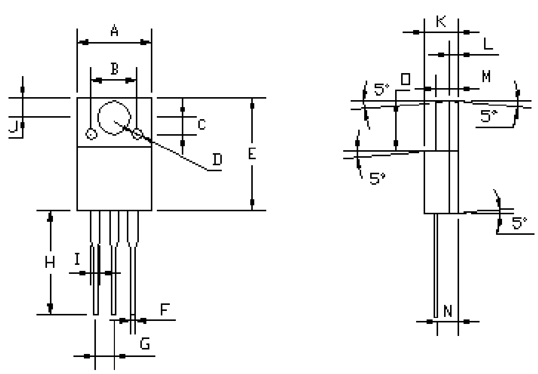
1. Top View 2. Side View



TO-220 DIMENSION				
DIM	MILLIMETERS		INCHES	
	MIN	MAX	MIN	MAX
A	10.00	10.50	0.394	0.413
B	3.24	4.44	0.128	0.175
C	2.44	2.94	0.096	0.116
D	3.565	4.315	0.140	0.170
E	0.68	0.92	0.027	0.036
F	1.115	1.485	0.044	0.058
G	2.345	2.715	0.092	0.107
H	13.49	14.31	0.531	0.563
I	4.475	5.225	0.176	0.206
J	1.15	1.39	0.045	0.055
K	27.78	29.62	1.094	1.166
L	2.175	2.925	0.086	0.115
M	0.297	0.477	0.012	0.019
N	8.28	8.80	0.326	0.346
O	14.29	15.31	0.563	0.603
P	6.01	6.51	0.237	0.256

TO-220F Mechanical drawing

1. Top View 2. Side View



TO-220F DIMENSION				
DIM	MILLIMETERS		INCHES	
	MIN	MAX	MIN	MAX
A	9.9	10.1	0.390	0.398
B	6.2	6.2	0.244	0.244
C	2.2	2.2	0.087	0.087
D	1.4	1.4	0.055	0.055
E	15.0	15.2	0.591	0.598
F	0.48	0.72	0.019	0.028
G	2.355	2.725	0.093	0.107
H	13.49	14.31	0.531	0.563
I	1.115	1.485	0.044	0.058
J	2.6	2.8	0.102	0.110
K	4.4	4.6	0.173	0.181
L	1.115	1.15	0.045	0.045
M	2.95	3.15	0.116	0.124
N	2.6	2.8	0.102	0.110
O	6.55	6.65	0.258	0.262

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