Laboratory Drill Rig Design for Bit Wear & Vibration Study

By

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Dissertation submitted in partial fulfillment of
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(Mechanical)

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Approved by,

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TRONOH, PERAK

MAY 2014

Certification of Originality

This is to certify that I am responsible for the work submitted in this project, that the original work is my own except as specified in the reference and acknowledgements, and that the original work contained herein have not been undertaken or done by unspecified sources or persons.

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(CALVIN YONG YEE ZHUN)

Abstract

Drilling operations is a costly operation and any factors that contribute to the delaying of work operation would be unwanted by the industry. Among the many factors that contribute to problems are bit wear and vibration. Besides currently there are no real time monitoring of bit wear in the oil and gas industry. The main objective of this project here is to design a safe laboratory scale test rig that is capable of assimilating the actual drilling operations and conditions out in the field. Thorough study of material selections and decision making processes such as the weighted evaluation matrix and also analytic hierarchy process (AHP) are used in order to complete the study and thus providing a proper conceptual design of the laboratory scale test rig. A design concept is also generated together with general static analysis of the designed concept. With the lab scale test rig, studies on the bit wear and also vibrations could be done and thus further optimization of drilling practices could be done at a lower cost rather than practicing out in actual drilling operations. This work would illustrate the advantages of varying the parameters for better drilling results in the oil field.

Acknowledgement

First and foremost I would like to give my utmost appreciation towards my supervisor and co-supervisor. AP Dr. Ahmad Majdi Abdul Rani as the supervisor and Dr Dereje Enjida Woldemichael as the co-supervisor have constantly guided me and supported me with the completion of this project. During the course of the completion of the project, there were constantly trips to the PETRONAS Twin Tower and also TERCEL Oilfield Products to meet with the operators to gain useful knowledge on the project. I would like to give my thanks to Mr Hassan of PCSB and also to Mr Mohamed Khalili for their useful knowledge on the study of the drilling bit and also the knowledge about the oil and gas industry. Without them, the project would not have gone through smoothly. Special thanks also to the YUTP team Mr Kharthigesan and Mr Muhammad Hariz for their useful input and also helpful ideas when completing this project. Lastly to my beloved family and friends who were constantly giving me the support mentally and physically, without them, I would not have succeeded.

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Chapter 1

Introduction

1.1 Project Background

The main component in the oil and gas industry is the hydrocarbons which are stored underneath the subsurface of the Earth. Hydrocarbons are used widely in our daily routines such as to power up vehicles, manufacturing plants, provide heat and many more. In order to retrieve these hydrocarbons from the Earth and produce it into products that can be used widely, Exploration and Production (E&P) processes are initiated. E&P process consist of six phases which are from Acquisition of Rights, Exploration, Appraisal, Development, Production, and Processing. The major part of the E&P process is the drilling process which is under the Exploration and Appraisal phase. When a certain geological structure has been identified by the geologist, exploration would be conducted and drilling will commence. Drilling operation is done of drilling rigs and the figure below shows an illustration of a rotary drilling rig.

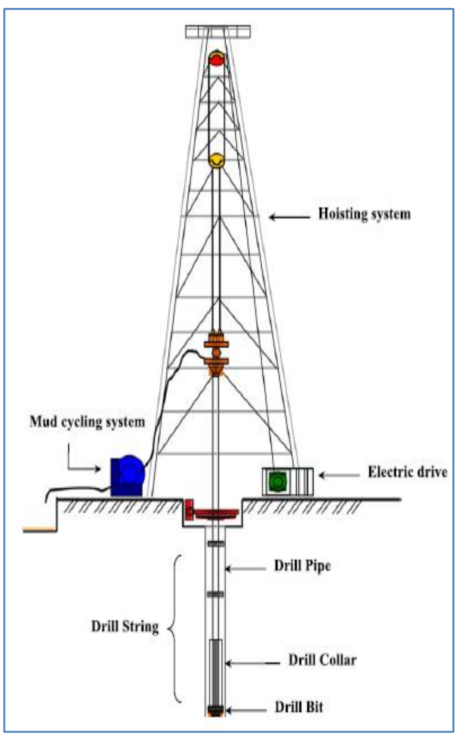


Figure 1: Illustration of rotary drilling rig

Drilling is an operation where it is conducted around the clock non-stop in order to avoid non-productive time (NPT) as time is very important when operating on rigs. The amount of cost spent in an operation is very dependent on the amount of time spent operating on the rig platforms. In order to decrease the amount of time spent operating on the rig platforms, ways of increasing drilling performances were being looked into. According to King et al. (1990), hydraulic optimization has an important part in the improvement of drilling bit performance. It is understand from their study that by optimizing the hydraulic systems of the drilling operations, rate of penetration also increases. Besides the hydraulic system, weight is also an issue when it comes to drilling operations. Optimum weight used in drilling will optimize the drilling penetration but too much weight applied when drilling would back-fire and destroy the bit and the bottom–hole assembly.

In order to study the optimization of the parameters used in the day to day drilling operation, a laboratory scale test rig is designed to simulate the actual drilling conditions out in the field. Laboratory drill rig is used in order to accelerate the development of Polycrystalline Diamond Compact (PDC) bits used for drilling oil and gas wells. According to studies, using the laboratory drill rig, assessments on bit cutter performance and drill string vibrations can be done and is based on actual drilling conditions. The figure below shows an example of a lab-scale drill rig.

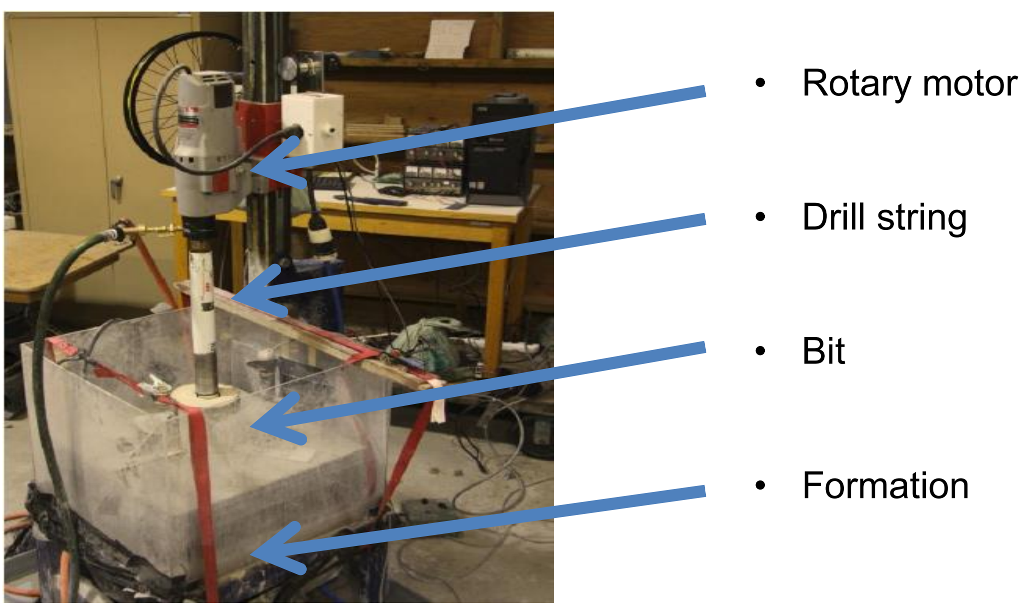


Figure 2: Example of a lab-scale drill rig

1.2 Problem Statement

Till date, even with the most advance of technology, there is currently still no real-time method to observe for bit wear. Bit wear is one of the limiting factors for drilling. Any drill bits underperforming means lower rate of penetration and thus leading to increase of cost and time spent on drilling the particular well. Besides that, if the industry were to run testing for bit wear during actual operations, it will be very costly to the industry. The industry has always faced challenges when it comes to drilling operations. The challenges include prediction of bit wear when drilling through certain formations and also in identifying the optimum drilling parameters when using particular design of bit.

1.3 Objectives

The objective of this project is to provide a laboratory scale drilling rig that is capable of doing bit testing. With the lab-scale drilling rig, only then it can function to aid in drilling optimization through a series of lab testing of bits. When designing the test rig, it is always important to design a safe operating test rig in order to run testing in a safe condition without injuring any personnel. Another objective at the end of the project is to execute Finite Element Analysis studies on design.

1.4 Scopes of study

The scope of study based on the objectives can be simplified as the following:

- Designing a test rig that manipulates with the drilling parameters such as the rotational speed and also the WOB which are the main contributors to the drilling vibration and bit wear.
- Ensuring that the test rig is able to withstand the amount of loads and stress when conducting tests.
- Ensuring the test rig is safe to be operated while doing testing.

Chapter 2

Literature Review

2.1 Drill bits

The drill bit is probably the most critical item of a rotary rig operation. It is the most refined of the rotary-rig tools, available in many styles, and is more highly specialized for every condition of drilling than any other tool on the rig. To select the proper bit, some information must be known about the nature of the rocks to be drilled. There are two main types of bits normally used for rotary drilling and have several variations within these types, primarily based on the cutting structure used for drilling the rock. These two types of drill bits normally used are as follow:

- Tri-cone Bits

Figure 3: Tri-cone bit

- Fixed Cutter Bits

Figure 4: Fixed cutter bit

The polycrystalline diamond compact (PDC), is a type of a fixed cutter bit and is one of the most important advances since their first production in 1976 according to Kate (1995). The PDC bit may have one of three basic profiles which are the short parabolic, shallow-cone, or parabolic. The figure below shows the three different profiles.

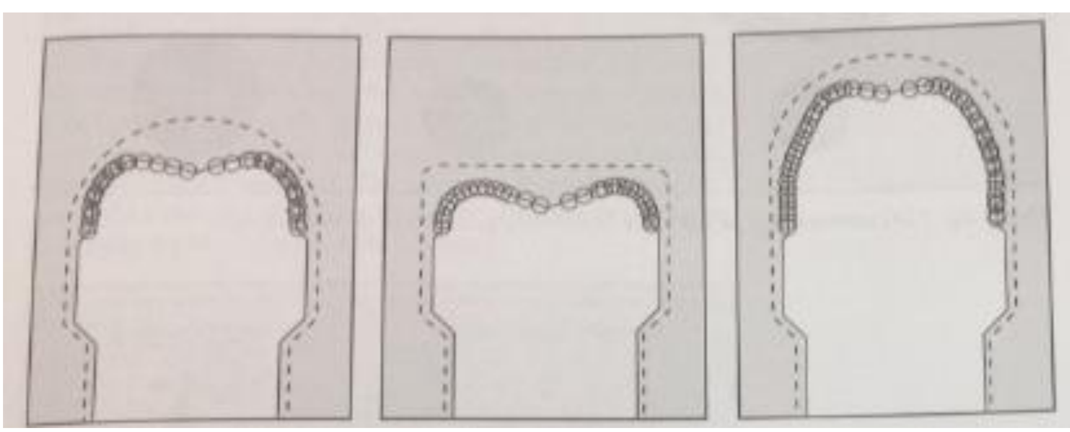


Figure 5: Short, Shallow-cone and Parabolic profiles of a PDC bit (The Bit, 1995)

2.2 PDC drill bit design

A drill bit design has a number of different features in order to obtain good drilling performances. According to Kerr (1988), features such as the number of cutters, type of cutters and angle of cutters are some of the examples of factors that affects the rate of penetration (ROP). Feenstra & D.H. Zijsling (1984) proposed that bit hydraulics is also another feature that is needed to be considered to contribute to a bit's performance. PDCs cut deeper than natural diamonds because the cutters are larger which produces more cuttings. A better hydraulic system is needed in order to wash the cuttings out from the annulus. Besides that, the cooling function of the drilling fluid is crucial because of the heat generated from the shearing of formation. Kate (1995) stated also in her book that the harder the formation, the more important the cooling function is to prevent the cutters from disintegrating. The softer the formation, tendency of bit balling would occur if bit hydraulics is not performing at its optimum level.

2.3 Weight-on-Bit (WOB)

Achieving the best performance of the bit all depends on properly altering the weight applied on the bit and also the amount of rotary speed used during a drilling operation. In general, the higher the rotating speed, the lower the weight on the bit or vice versa. According to many runs in the field or even tests in the laboratory, the optimum combination of weight and rotary speeds varies from different hardness of the formation. According to Kate (1995), PDC bits can drill very fast in soft, nonabrasive formations as the cutters shear deeply into the formation on each rotation. In this case, one PDC bit may drill for typically 300 hours or more and for several thousand feet. The bit performance depends on properly adjusting the WOB and rotary speed. Harder formations would require higher WOB in order to crush the stones but may backfire and damage the bit itself. Besides damaging the bit, WOB also affects the vibration behavior of the drillstring according to Ghasemloonia, Rideout, & Butt (2010).

2.4 Laboratory Drill Rig Testing

Through the years of PDC development laboratory testing has been used to assess performance. Various laboratory drilling analogs have been tried including lathe, vertical turret lathe, planer and mechanical testing. According to J. Lund and his team in the year 2007, full scale laboratory drilling test facilities have been built by most drill bits companies. However, because of the scale of the equipment required to undertake this work, the testing are very costly to the owners of the equipment or the contracting party.

The results of experiments were given in the terms of torque and weight generated at various penetrations rates in different types of rocks. At the same time, the dull grading of bits is also determined from the experiments. These are the results that a laboratory drill rig testing provides and also wanted by the companies and the industry. This shows that lab testing is used to obtain the most reliable simulation of drilling operations. There are a lot of benefits from this lab scale drill rig testing. J. Lund and his team also mentioned that the drill rig testing also produces a cutter path that is very similar to a full scale drill bit in that the cutters are rotated in a circular path around the center of rotation of the bit. It is also more compliant ad it is a better representation of the downhole drilling environment, and ultimately, lab scale drill rig testing is more cost saving as compared to the full scale lab facilities.

The drill rig capacities used in their study are shown in the table below.

Table 1: Drill rig capacity used in the study by J.Lund and his team

Parameter	Capacity
Max rotary power	44.7 kW
Vertical feed rate	0.3 - 67 m/hr
Stroke	1.02 m
Max vertical force	164.6 kN
Rotational speed	40 - 1500 rpm
Torque on bit	1898 N.m @ 100 rpm (14.2 kW) 879 N.m @ 500 rpm (28.3 kW) 439 N.m @ 1000 rpm (35.8 kW)
Coolant flow	83.3 l/min max flow - closed loop system
Rock size	0.91 m x 0.91 m x 0.91 m (cube)

2.5 Designing of Laboratory Drill Rig

During the designing stage of the laboratory drill rig, there are certain specifications and ideas that are needed to be considered. The considerations include the rotary motion of the drilling movement, the downward movement, and the method to measure the vibration of the drilling movement. A. Ersoy and M.D. Walter mentioned in their study where to facilitate the testing of both PDC cutters and roller cone bits, there is a need for the aid of servo-hydraulic system to provide the thrust and the electric servo motor to provide the rotary motion. In another study by A. Ablahi in 2011, when designing the laboratory drill rig, the rotation of the drill bit and the action of it pressing against the rock materials should provide the outcome results that show the extent of rock materials that are removed and also the degree of bit wear can be analyzed. There are two types of modes that are used as a benchmark for designing. These two modes are:-

- Rate of penetration (ROP) and rotation per minute (RPM) fixed; Vertical thrust (WOB) varied to sustain the ROP.
- Vertical thrust and RPM fixed; ROP to be measured.

2.6 Weighted Evaluation Matrix

In the real world, making decisions is both important and difficult. In an organisation, a person must make critical decisions that all stakeholders would have confidence in, and those decisions are somehow justifiable. Besides that documenting the decisions made in structured ways is important to ensure that other people will be able to understand the reasons for having made a decision for future referencing. A weighted evaluation matrix is a tool used to compare alternatives with respect to multiple criteria of different levels of importance. It can be used to rank all the alternatives relative to a “fixed” reference and thus create a partial order for the alternatives. There are often many different criteria that need to be considered in making a decision. The most important step is to define the correct criteria, and to evaluate the choice with respect to those criteria as precisely as possible. The ability to use the weighted matrix means that one is able to make and take decisions more confidently and rationally as compared to those that do not use a proper strategized structure to do decision making.

2.7 Analytic Hierarchy Process

According to Thomas L. Saaty, decisions involve many intangibles that need to be traded off. For that they have to be measured alongside tangibles whose measurements must also be evaluated as to, how well, they serve the objectives of the decision maker. In this case, the Analytical Hierarchy Process or in short AHP is a theory of measurement using the pairwise comparisons and relies on the judgements of experts to derive priority scales. Decision making, for which we gather most of our information, has become a mathematical science today (Figuera et al., 2005). Decision making involves many criteria and sub-criteria used to rank the alternatives of a decision. Not only does one need to create priorities for the alternatives with respect to the criteria or sub-criteria in terms of which they need to be evaluated, but also for the criteria in terms of a higher goal, or if they depend on the depend on the alternatives, then in terms of the alternatives themselves (Saaty, T.L., 2008). In his study on AHP, he also includes the decomposition of the AHP steps. The following are the steps taken in making a decision in an organized way that generate priorities.

I. Defining the problem and determining the kind of knowledge sought.
II. Structuring the decision hierarchy from the top with the goal of the decision, then the objectives from a broad perspective, through the intermediate levels to the lowest level.
III. Constructing a set of pairwise comparison matrices. Each element in an upper level is used to compare the elements in the level immediately below with respect to it.
IV. Using the priorities obtained from the comparisons to weigh the priorities in the level immediately below. Doing this for every element and then for each element in the level below add its weighed values and obtain its overall or global priority.
V. Continue this process of weighing and adding until the final priorities of the alternatives in the bottom most level are obtained.

The AHP method uses a set of fundamental scale of absolute numbers in order to rank the importance of one element over another element. The following table below showcases the set of numbers scaled from one to nine with the description of each number. This numbering was made famous by Saaty's study.

Table 2: The fundamental scale of absolute numbers used in Saaty's study.

Intensity of Importance	*Definition*	*Explanation*
1	Equal Importance	Two activities contribute equally to the objective
2	Weak or slight	
3	Moderate importance	Experience and judgement slightly favour one activity over another
4	Moderate plus	
5	Strong importance	Experience and judgement strongly favour one activity over another
6	Strong plus	
7	Very strong or demonstrated importance	An activity is favoured very strongly over another; its dominance demonstrated in practice
8	Very, very strong	
9	Extreme importance	The evidence favouring one activity over another is of the highest possible order of affirmation
Reciprocals of above	If activity i has one of the above non-zero numbers assigned to it when compared with activity j, then j has the reciprocal value when compared with i	A reasonable assumption
1.1–1.9	If the activities are very close	May be difficult to assign the best value but when compared with other contrasting activities the size of the small numbers would not be too noticeable, yet they can still indicate the relative importance of the activities.

Chapter 3

Methodology

3.1 Process Flow of the Project

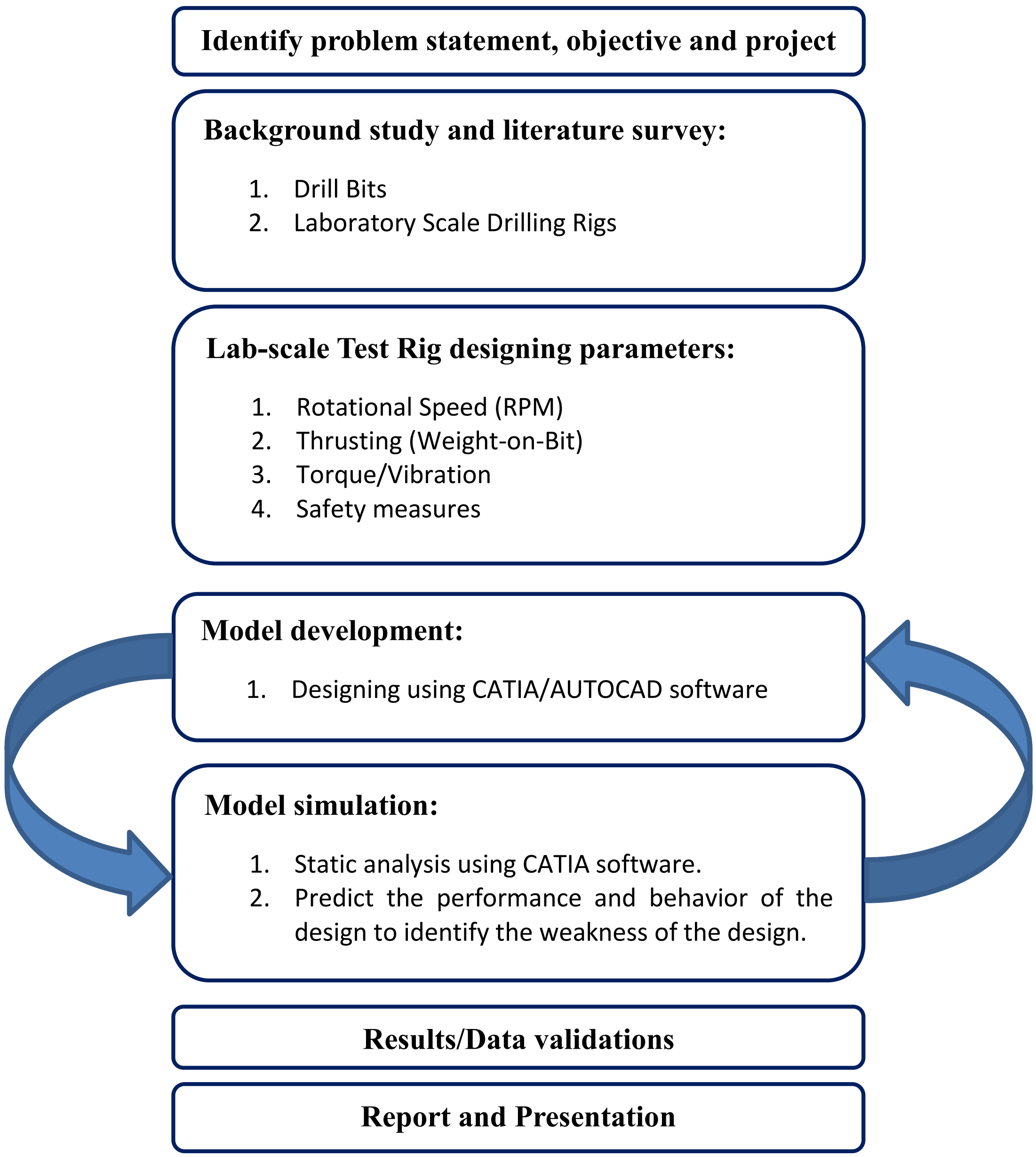


Figure 6: Workflow of the project

3.2 Gantt Chart and Key Milestones

Table 3: Gantt chart and key milestones

No	Week / Activities	1	2	3	4	5	6	7		8	9	10	11	12	13	14
1	Literature Review															
2	Listing of Materials and Equipment															
3	Selection of Material and Equipment				●	- List of material and equipment are obtained.										
4	Designing of Concept															
5	Structure Analysis of Designed Concept											●	- Stress analysis is generated.			
6	Finalized Design Concept						- First generation of lab-scale test rig design is produced.						●			

● Key Milestone

3.3 Concept Generation

In concept generation, there are three major steps which are the decomposition process of the complex system, generation of morphology chart, and also the conceptual designs sketching based on the morphology chart. The decomposition process is conducted in order to break down complex system into smaller units in order to manage and understand the systems better. Decomposition is divided into two categories which are the physical and functional decomposition. Both these two categories have their own objectives which will be explained in the following sub-sections.

3.3.1 Functional Decomposition Chart

Functional decomposition is use to identify the system designs of the project. Using the functional decomposition chart, we can easily showcase the systems that are used or systems that is needed in order for the project to work. The systems that are used in this project are shown in the chart below.

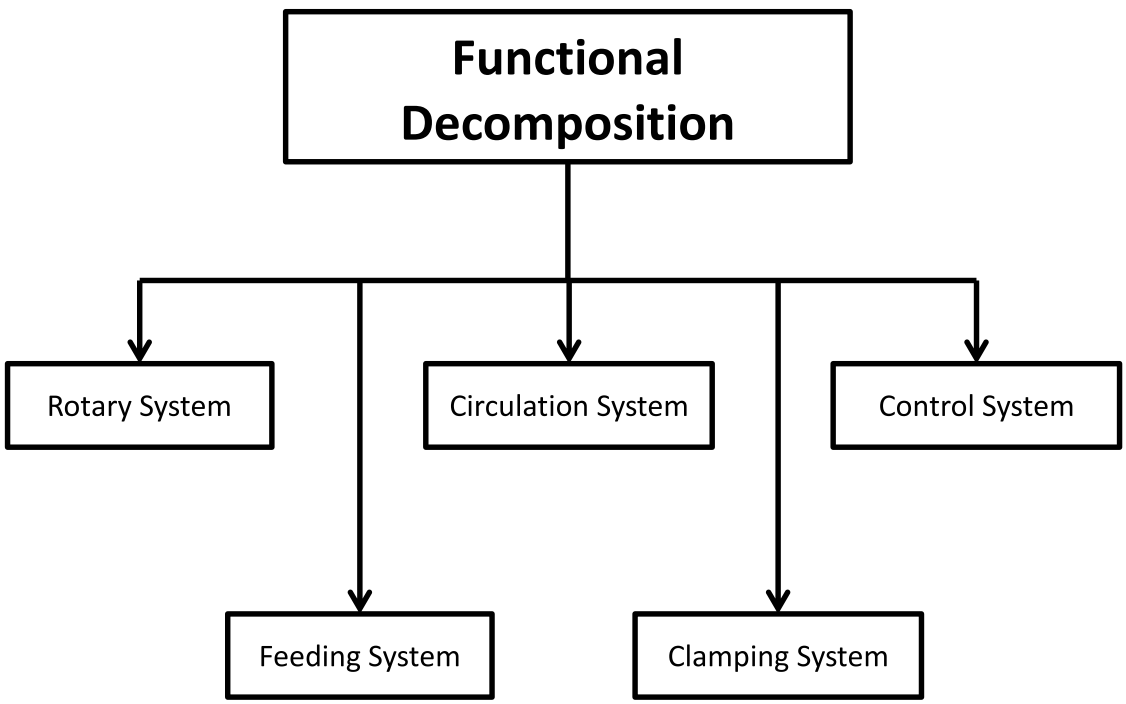


Figure 7: Functional decomposition chart

From the chart above, the functional decomposition is broken down to five types of systems. The five systems are the rotary, circulation, control, feeding and clamping systems. Below is a table that justifies each system's functions.

Table 4: Types of system and its justification of the test rig

Types of system	System Justification
Rotary system	• The rotary system consists of the rotating component that holds onto the drill string and also the drill bit. • The rotary system gives the test rig the rotating motion of the drilling test. • The rotary system is the main system in the test rig as it resembles the drilling operation on the rigs off and onshore.
Feeding system	• The feeding system resembles the hoisting system on a drilling rig. • This system is responsible of pushing the bit against the formation test sample or vice versa where the test sample is pushed against the bit.
Circulation system	• The circulation system is not similar to what the actual drilling rig where it actually brings out the cuttings out of the hole. • This circulation system is to provide the cooling process of the bit when the bit is rotating at a high speed against the sample formation.
Clamping system	• The clamping system is a simple mechanism where it holds on to the sample formation. • This system is used in order to prevent the testing sample to rotate together with the bit when the bit bites onto the sample.

Control system	• The control system consists of the manipulation of the parameters that will be used in conducting the experiment. • Controls such as the variation of rotation speed, vibrating motion sensor, and also the amount of weight that is applied on the test sample.

3.3.2 Physical Decomposition Chart

Physical decomposition is to identify the components or subassemblies, with the accurate description of the interaction and joint between them. The physical decomposition breaks down the functional decomposition to its respective operating components. The physical decomposition chart of this project is as shown below.

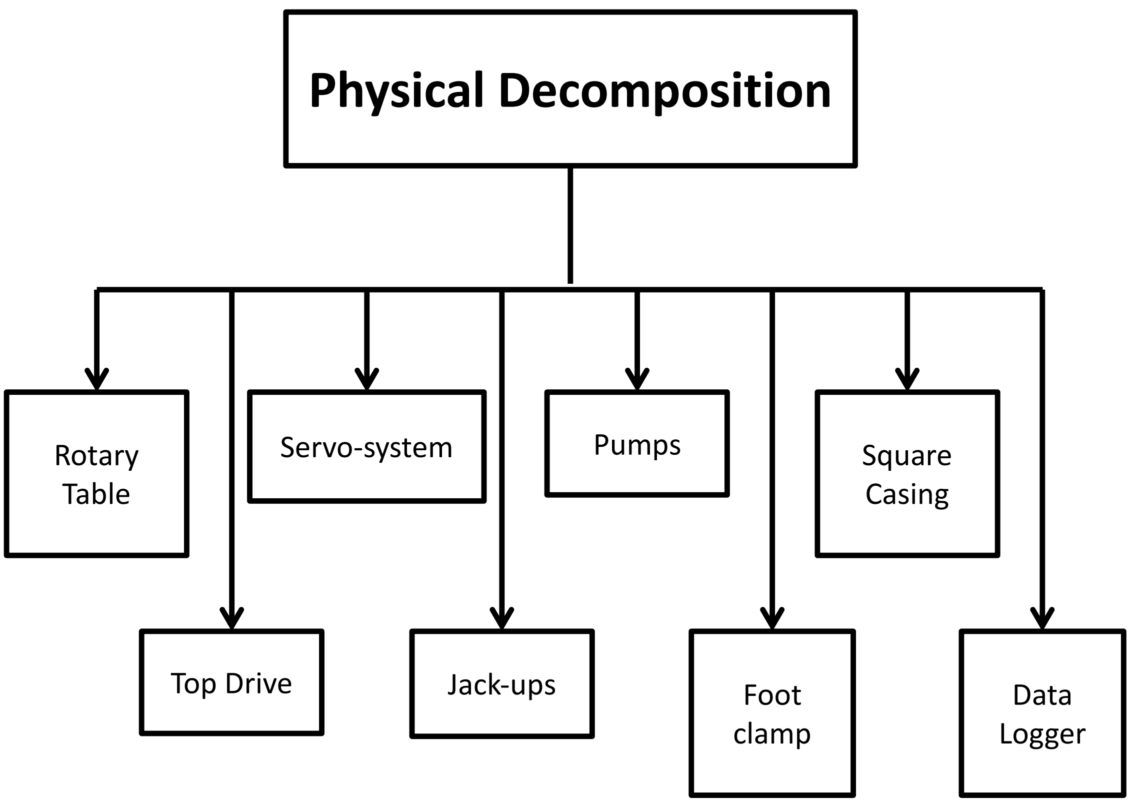


Figure 8: Physical decomposition chart

3.3.3 Morphology Chart

The morphology chart is actually a tool to list out the possible options based on the functions listed out. The morphology chart eases the later selecting process as it provides a simpler and understandable platform for easier referencing. Below are three tables listed for three different types of system which are the rotary system, feeding system and also the clamping system. For this project, only three systems are considered while the remaining two systems such as the control system and also the circulation system will be continued in the future work planning.

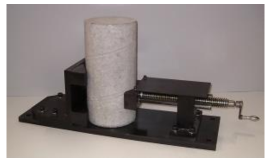
Table 5: Morphology chart for rotary system

Functions	Option 1	Option 2	Option 3
Rotation from table	Precision rotary table 	HAAS CNC rotary tables 	Kelly Bushing 
Rotation from top drive	Hydraulic motors (consist of quill)	CNC lathe machine attached at the top	
Drill string holder	Screw-on (Box-pin)	Slip-in holder	Clamps

Table 6: Morphology chart for feeding system

Functions	Option 1	Option 2	Option 3	Option 4
Up and down motions	Jack-ups	Servo-system	Top drive	Manually operated (shaved ice)

Table 7: Morphology chart for clamping system

Functions	Option 1	Option 2	Option 3
Holding samples	Rock Specimen Holder 	Foot clamp 	Band clamps 
Base of the drilling rig	Square base	Circular base	

Chapter 4

Results and Discussion

4.1 Go/No-Go screening

For this project, a series of decision making methods are used in order to obtain the best equipment to build the test rig. From the morphology chart generated before, firstly a GO/NO-GO screening is used. A GO/NO-GO screening is used in order to eliminate those items that are either not feasible or irrelevant in designing the lab-scale test rig. With the morphology chart obtained, a total number of 432 options were generated. After the GO/NO-GO screening is done from the morphology chart, the morphology chart would look something like this and thus giving us lesser options to include in the decision making.

Table 8: GO/NO-GO screening for rotary system

Functions	Option 1	Option 2	Option 3
Rotation from table	Precision rotary table 	HAAS CNC rotary tables 	~~Kelly Bushing~~ 
Rotation from top drive	Hydraulic motors (consist of quill)	CNC lathe machine attached at the top	
Drill string holder	Screw-on (Box-pin)	Slip-in holder	~~Clam[illegible]~~

Table 9: GO/NO-GO screening for feeding system

Functions	Option 1	Option 2	Option 3	Option 4
Up and down motions	Jack-ups	Servo-system	Top drive	~~Manually [illegible] ([illegible]aved [illegible])~~

Table 10: GO/NO-GO screening for clamping system

Functions	Option 1	Option 2	Option 3
Holding samples	Rock Specimen Holder 	Foot clamp 	Band clamps 
Base of the drilling rig	Square base	Circular base	

4.2 Weighted Evaluation Matrix

From the above screening done, it is seen that there is a significant drop in number of possible options which was from a total number of 432 options to only 96 options. Using this new number of options generated, weighted evaluation matrix is used. In weighted evaluation matrix, three design criteria are used which are Feasibility, Operability, and Reliability. A number scale is given to each designing criteria to give the materials value in order to calculate for better selection. Below shows the evaluation for the design criteria.

Table 11: Design criteria evaluation for feasibility

11-point Scale	**Feasibility**
0	• Items and equipment are difficult to acquire/manufacture.
1 2 3 4	. . . .
5	• Items and equipment can be manufacture and acquired within the time limit of less than 6 months.
6 7 8 9	. . . .
10	• Items and equipment can be obtained off the market shelf

Table 12: Design criteria evaluation for operability

11-point Scale	**Operability**
0	• Requires a very big space and not safe to use (Requires a certain skill set that needs training)
1 2 3 4	. . . .
5	• Moderate spacing usage and safe to use.
6 7 8 9	. . . .
10	• Optimum space usage and safe and easy to operate.

Table 13: Design criteria evaluation for reliability

11-point Scale	**Reliability**
0	• High expectation of system breakdown accompanied with major effects and high probability of failure.
1 2 3 4	. . . .
5	• Average expectation of system breakdown accompanied with moderate effects and average probability of failure.
6 7 8 9	. . . .
10	• Low expectations of system breakdown accompanied with minor effects and low probability of failure.

From the tables of design criteria evaluation, the weighted evaluation matrix tables are generated for each systems as shown below.

Table 14: Table of weighted evaluation matrix for rotary system

Criteria	Weight	Precision Rotary Table		CNC rotary table		Hydraulic motors		CNC rotary attached from top	
Feasibility	0.45	5	2.25	5	2.25	7	3.15	7	3.15
Operability	0.3	6	1.8	5	1.5	7	2.1	6	1.8
Reliability	0.25	5	1.25	5	1.25	7	1.75	6	1.5
Total			5.3		5		7		6.45

Table 15: Table of weighted evaluation matrix for rotary system (holder)

Criteria	Weight	Screw-on (Box-Pin)		Slip-in holder	
Feasibility	0.45	8	3.6	7	3.15
Operability	0.3	7	2.1	7	2.1
Reliability	0.25	8	2	6	1.5
Total			7.7		6.75

Table 16: Table of weighted evaluation matrix for feeding system

Criteria	Weight	Jack-ups		Servo-system		Top-drive system	
Feasibility	0.45	6	2.7	7	3.15	5	2.25
Operability	0.3	6	1.8	7	2.1	6	1.8
Reliability	0.25	4	1	8	2	7	1.75
Total			5.5		7.25		5.8

Table 17: Table of weighted evaluation matrix for clamping system

Criteria	Weight	Rock Specimen Holder		Foot Clamp	
Feasibility	0.45	6	2.7	7	3.15
Operability	0.3	6	1.8	5	1.5
Reliability	0.25	7	1.75	6	1.5
Total			6.25		6.15

4.3 Analytic Hierarchy Process

Besides using the weighted evaluation matrix, a method called the Analytic Hierarchy Process was also used to verify the selection of the equipment. Using the number scale that Saaty and his team provided in their study, the table below shows the AHP matrices generated and also the statistical scores of the equipment selected. The points are given accordingly to the importance that one equipment would operate better over the other suggested equipment.

Table 18: AHP matrix for rotary system

	Precision rotary table	CNC rotary tables	Hydraulic motors (Top drive)	CNC rotary attached from the top	Sum	Statistical Score
Precision rotary table	1	2	1/9	1/7	205/63	0.095
CNC rotary tables	1/2	1	1/7	1	37/14	0.077
Hydraulic motors (Top drive)	9	7	1	2	19	0.552
CNC rotary attached from the top	7	1	1/2	1	19/2	0.276

Table 19: AHP matrix for rotary system (Drill string holder)

	Screw-on (Box-pin)	Slip-in holder	Sum	Statistical Score
Screw-on (Box-pin)	1	8	9	0.89
Slip-in holder	1/8	1	1.125	0.11

Table 20: AHP matrix for feeding system

	Jack-ups	Servo-system	Top-drive system	Sum	Statistical score
Jack-ups	1	1/8	1/3	35/24	0.07
Servo-system	8	1	6	15	0.727
Top-drive system	3	1/6	1	25/6	0.203

Table 21: AHP matrix for clamping system

	Rock Specimen Grinding Machine	Foot Clamp	Sum	Statistical Score
Rock Specimen Holder	1	4	5	0.8
Foot Clamp	1/4	1	1.25	0.2

From the above tables and comparing the results obtained from the weighted evaluation matrix and the AHP matrices, it is determined that the highlighted equipment are to be selected to construct the initial phase of the laboratory drilling test rig. The AHP matrices generated verified the validity of the weighted evaluation matrix and thus shows the similarity in the usage of two different decision making approach. From the weighted evaluation matrix and AHP method, the total score calculated shows clearly that some of the equipment or materials stands out to be used for designing the lab scale test rig. A table of the selected equipment generated by the weighted evaluation matrix is shown below.

Table 22: Selected equipment using weighted evaluation matrix

System	Equipment
Rotary system	Hydraulic motors and screw-on
Feeding system	Servo-system
Clamping system	Rock specimen holder

4.4 Selection of Specific Equipment for Different Systems

Now that all the decision making for the equipment used in the different systems were selected, specifications of the equipment are to be decided in order to be used for future fabrication. The designing specification of each systems were determined and is shown below. The designing of the lab-scale test rig is scaled down from what the actual offshore oil rig is operating on.

Table 23: Design specification of the lab-scale test rig

Parameter	Specifications
Max rotational speed	2400rpm
Vertical feed rate	0.3 – 60m/hr
Max vertical force	Approximate at 100kN
Rock sample size	3inch – 6inch diameter

4.4.1 CATIA Assembly Drawing

From the previous sections, the decision making process was showcased and equipment are determined. For this section, the overall design specification of the design concept and the CATIA assembly drawing are shown as follow.

Table 24: Specification of the overall structure of the lab-scale test rig

Parameter	Specification
Structure base	1.5m(L) x 1.0m(W)
Height of structure	1.75m

The drawing consist of the hydraulic motor, servo-hydraulics, rock specimen holder, structure base and also the rock sample.

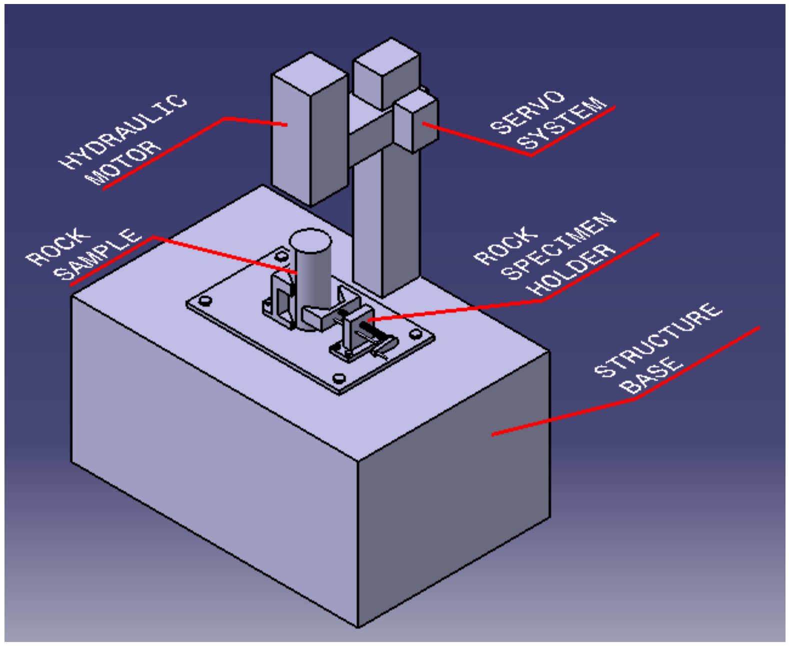


Figure 9: Isometric view of the design

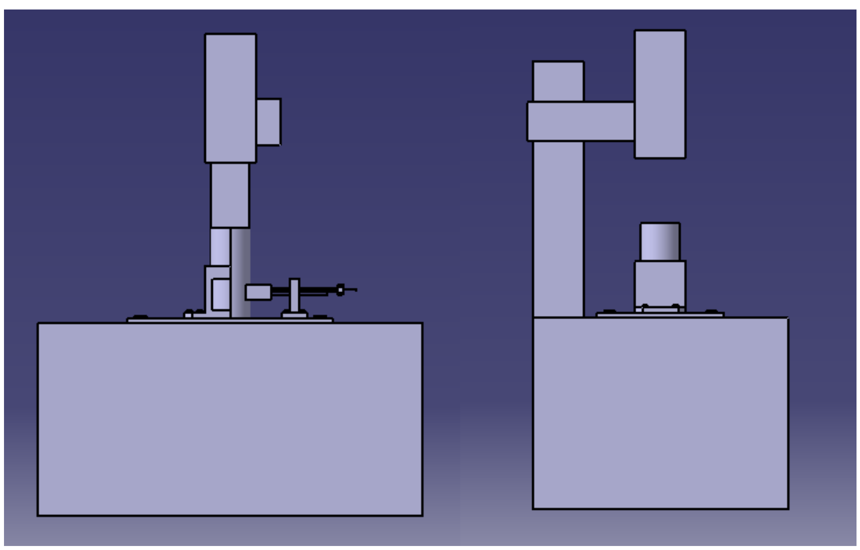


Figure 10: Front and left view of the design

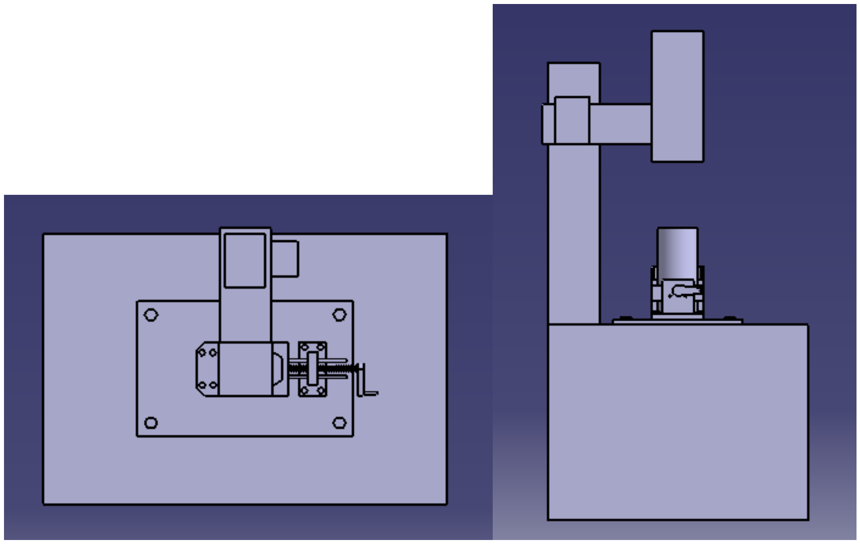


Figure 11: Top and right view of the design

4.4.2 Hydraulic Motor Selection

Firstly for the rotary system, different types of hydraulic motors are found off the internet and comparisons between each type of hydraulic motors are made based on the design criteria.

Table 25: Morphology chart for the selected types of hydraulic motors

	Option 1	Option 2	Option 3	Option 4	Option 5	Option 6
Hydraulic motors	 TC SERIES SMALL FRAME LSHT MOTORS	 TJ SERIES MED. FRAME LSHT MOTORS	 TG SERIES LARGE FRAME LSHT MOTORS	 MTE Hydraulics 400 Series	 Roller bearing hydraulic motors 5000/5100 SERIES	 Bushing Hydraulics motor 257 SERIES

Based on the six options above, hydraulic motors were reviewed from three different companies namely Parker Hydraulics, MTE Hydraulics and also PERMCO. All these selected hydraulic motors are initially selected based on the availability of the motor in the market. However selecting the best motor for the requirement of this project is necessary in order to provide the best performance from the lab-scale testing rig. Hydraulic motors are required to operate to a maximum rotational speed of 2400. Higher torque value of the motor also indicates that the motor can provide a better torque value at the bit when testing is being run. The table below summarizes the maximum rotational speed and the maximum torque value that the motor can provide.

Table 26: Summary of maximum rotational speed and torque value of hydraulic motor

	Option 1	Option 2	Option 3	Option 4	Option 5	Option 6
Hydraulic motors	TC SERIES SMALL FRAME LSHT MOTORS	TJ SERIES MED. FRAME LSHT MOTORS	TG SERIES LARGE FRAME LSHT MOTORS	MTE Hydraulics 400 Series	Roller bearing hydraulic motors 5000/5100 SERIES	Bushing Hydraulics motor 257 SERIES
Max rpm	902rpm	1024rpm	660rpm	2500rpm	2400rpm	2400rpm
Max torque	Up to 306.1 Nm	Up to 648Nm	Up to 1428Nm	Up to 1032Nm	Up to 1530Nm	Up to 1265Nm
Price (Approx.)	USD 74.96	USD329.90	USD550	USD400	USD599	USD425

Based on the summarized table, options 1 to option 3 are eliminated as the targeted rotary speed is less that the then decided designed specification which is at 2400rpm. Whereas options 4 to 6 are within range. The torque values of options 4 to 6 shows that the MTE hydraulics 400 series are lower than the ones offered by PERMCO, thus eliminating the possible option 4. A comparison was made between the benefits of using a roller bearing motor and the bushing hydraulics motor. Bushings are a sleeve that is usually made of soft semi-porous material to hold the lubricant. Roller bearings normally are of higher quality as compared to the bushing motors. This is because of the bushes that do not hold lubricant as well as bearings do which means that they will fail more easily as compared to the roller bearing motors. From the design specification of the hydraulic motor, option 5 which is the 5000/5100 series PERMCO roller bearing motor stands out more as the chosen equipment for the rotary system. The specifications and pricing list of each equipment can be referred in the appendices.

4.4.3 Servo System Selection

From the selection process in the previous section, the servo system is the choice for the feeding system in the project. Different types of servo related systems are gathered from the market and further comparisons were made to get the final choice of equipment. The following is a table of the equipment of choice and their respective specifications.

Table 27: Types of servo related systems with their specification and approximate cost

No	Type	Price (USD)	Max Output Thrust (kN)	Max Speed (mm/s)
1	EMG-ESZ electric servo cylinder	Approximate at 200	100	30
2	TOX Electric Power Module	Approximate at 1800	100	100
3	Parker ETR Series	Approximate at 199	100	729 – 972
4	Tsubaki Emerson Power Cylinder – T series/ Eco series	Approximate at 400	117	30 – 36

As stated in the previous sections, the output thrust or weight acting on the bit should be approximate at 100kN. All the suggested types of servo system provides the amount of required output thrust. However, there is a big contrast in the speed rate of each types of servo systems. The required vertical feed rate for the project is ranging from 0.1mm/sec to 20mm/s. This numbers are referenced from the laboratory scale drilling test rig used in Lund's study. From the above table, the Parker ETR series and TOX Electric Power Module has the highest maximum speed which is not necessary in the usage of this project. A better comparison would be between the EMG-ESZ electric servo cylinder and also the Tsubaki Emerson Power Cylinder. Their maximum speed rating are more considerable in this project as their range of speed are from 30 – 30mm/s. The choice of servo system to be chosen for the vertical thrust movement in the feeding system is finally then decided based on the price of each equipment. The Tsubaki Emerson Power Cylinder is more preferable even when the price is slightly higher than the ESZ electric servo cylinder. This is because the latter is currently unavailable in the market. However in the future, the electric servo cylinder can always be a second choice option whenever there is a need to change the equipment.

4.4.4 Material Selection for Manufacturing In-House Equipment

For the in-house manufacturing of equipment such as the structure base, feeder to hold the hydraulic motor and the servo-hydraulic motor, screw-on bit holder and also the rock specimen holder, material of the equipment are to be determine. In order to decide which materials are to be used to manufacture, the mechanical properties are listed down as follows for easier reference and selection. The tables below shows the different types of material along with the properties of each materials. Following the listed properties of each material, finite element analysis are done in order to differentiate the strength of the materials used.

Table 28: Mechanical properties of the suggested materials used for manufacturing in-house equipment

No	Material	Elastic Modulus (GPa)	Tensile Strength,Yield (MPa)	Ultimate Tensile Strength (MPa)
1	Iron	70	310	413
2	Carbon Steel	210	415	540
3	Stainless Steel	200	215	505
4	Monel 600	207	310	655

4.4.4.1 Finite Element Analysis

After completing the designing using the CATIA software, the design is put through a generative structural static analysis. This is to determine which type of material that is to be used for the manufacturing. One critical part of the structure is chosen for the analysis and the most critical part of the test rig structure is shown in the picture below.

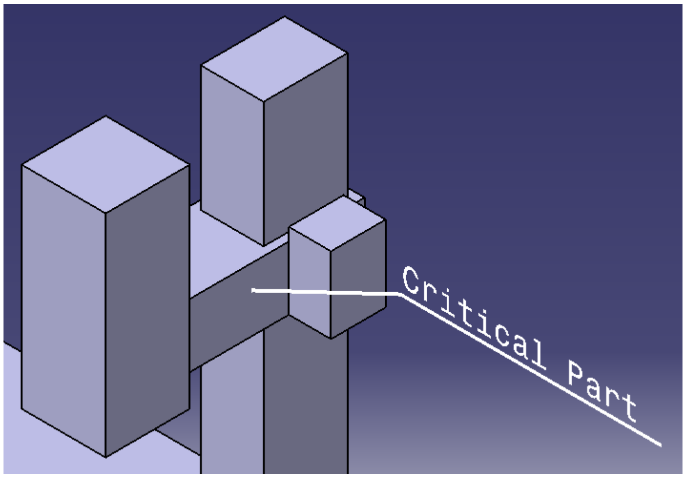


Figure 12: Critical part of the test rig

This static analysis consist of the deformation of the part where the force is applied, the Von Mises stress analysis and also the translational displacement vector. The applied force is 100kN on the critical part. The reasoning behind the 100kN force applied on the critical part is that the force applied is a resemblance of the weight that is put on the drill bit in the drilling operations. Besides that based on the study of Lund and his team, the amount of vertical force applied is from the range of 100kN to 164kN. The four different types of materials go through the same analysis and results were obtained. Deformation of the four different types of material after all respective simulations shows a similar pattern of deforming. A screen shot of the deformation is shown in the figure below.

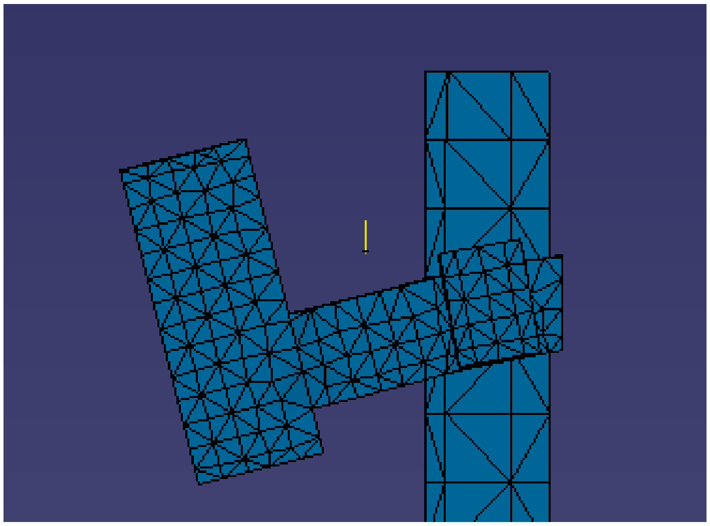


Figure 13: Deformation of structure

A) Iron

Using the designated material iron properties from the CATIA software material library, the iron used is the Gray Cast Iron 4.5% ASTM A-48. It has a Young's Modulus value of 200GPa, Poisson ratio of 0.266, density of 7860kg/m^3, and a yield strength of 250MPa. The results of the simulation is shown below.

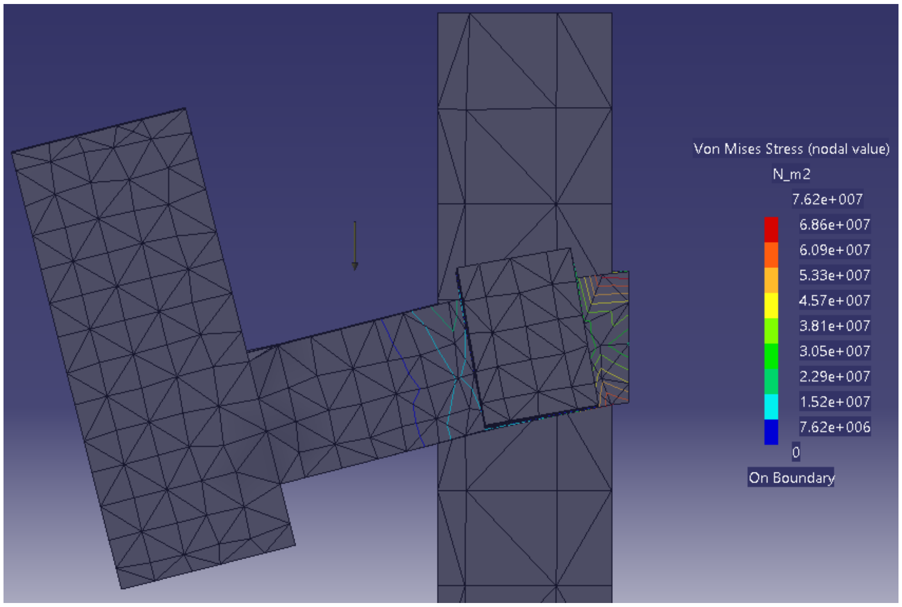


Figure 14: Von Mises Stress value (Iron Analysis)

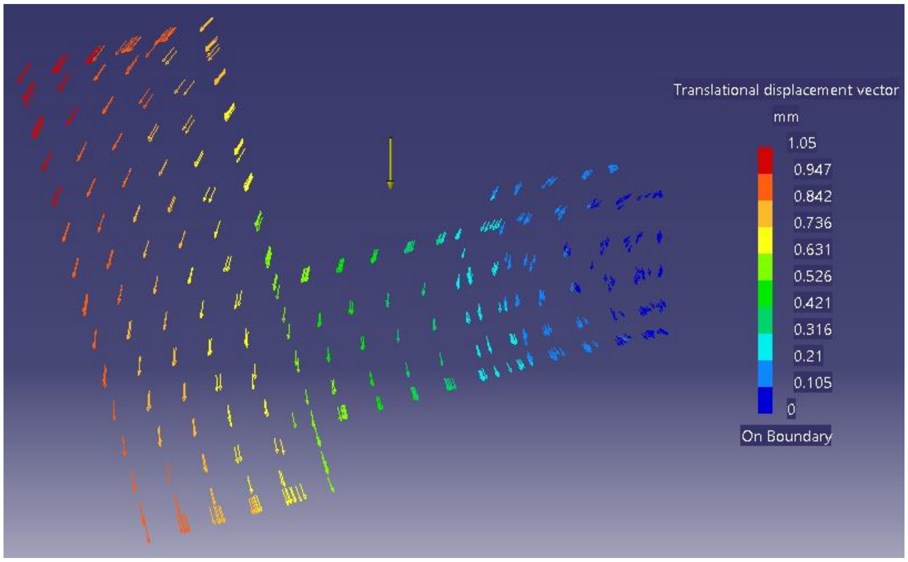


Figure 15: Translational displacement vector (Iron analysis)

B) Carbon Steel

Carbon steel has a Young's Modulus value of 210GPa, Poisson ratio of 0.29, density of 7870kg/m^3, and a yield strength of 415MPa. The results for carbon steel from the simulation are as shown below.

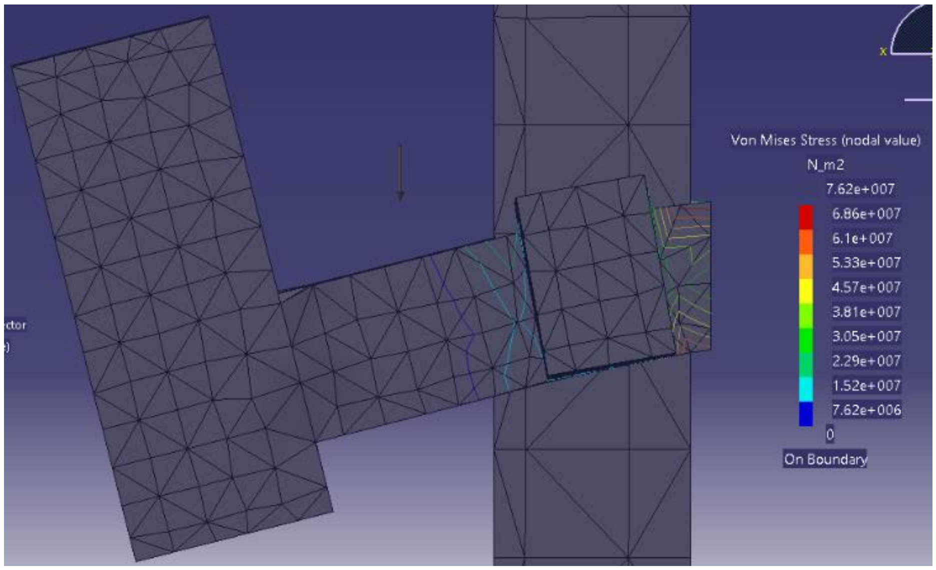


Figure 16: Von Mises Stress value (Carbon steel analysis)

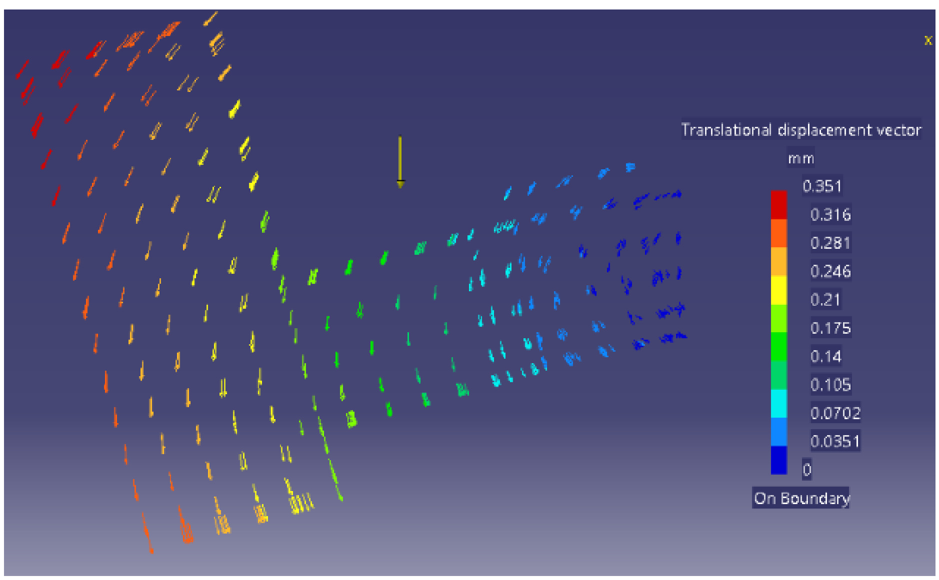


Figure 17: Translational displacement vector (Carbon steel analysis)

C) Stainless Steel

Stainless steel has a Young's Modulus value of 193GPa, Poisson ratio of 0.29, density of 8000kg/m^3, and a yield strength of 215MPa. The results for stainless steel from the simulation are as shown below.

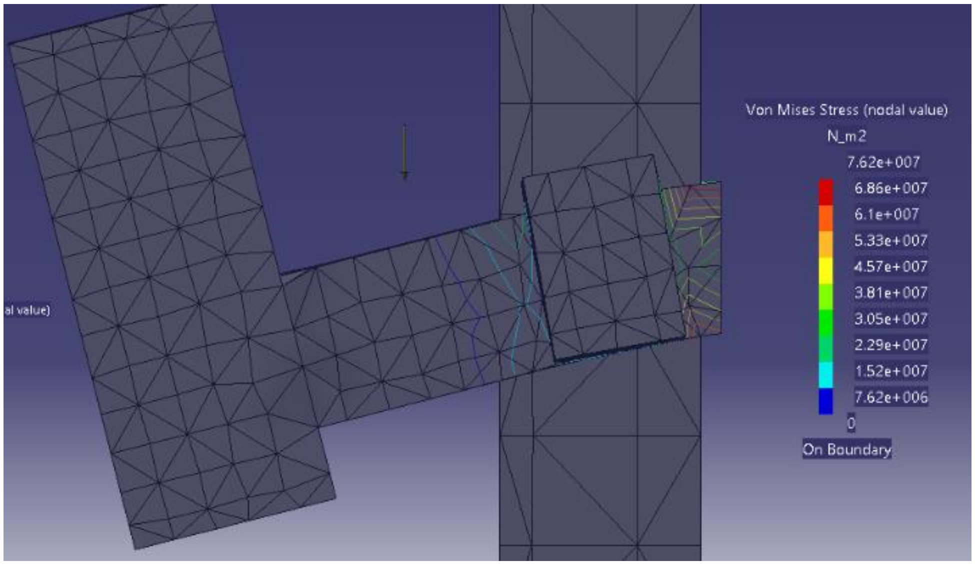


Figure 18: Von Mises Stress value (Stainless steel analysis)

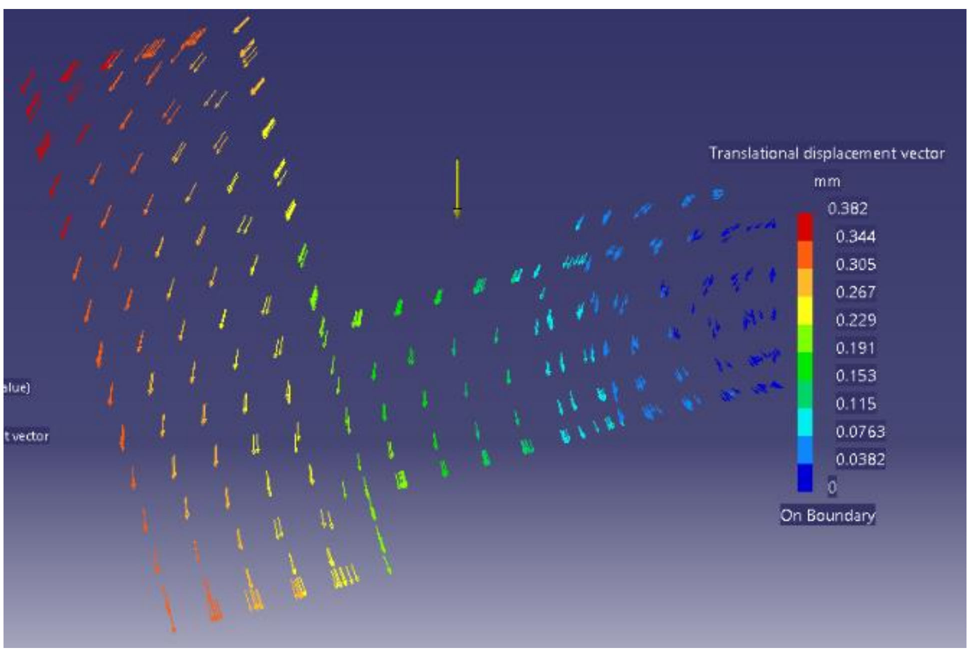


Figure 19: Translational displacement vector (Stainless steel analysis)

D) Monel 600

Monel 600 has a Young's Modulus value of 207GPa, Poisson ratio of 0.29, density of 8470kg/m^3, and a yield strength of 310MPa. The results for Monel 600 from the simulation are as shown below.

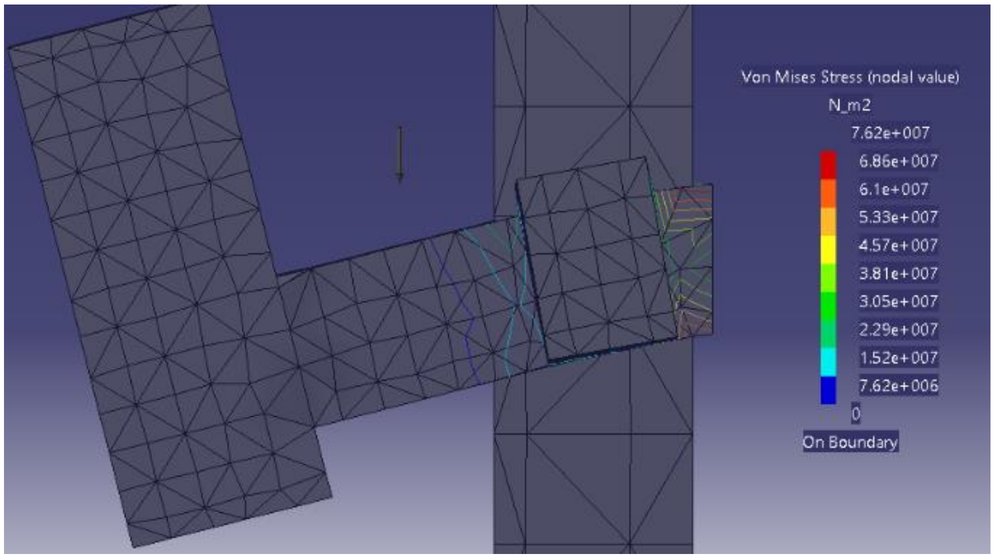


Figure 20: Von Mises Stress value (Monel 600 analysis)

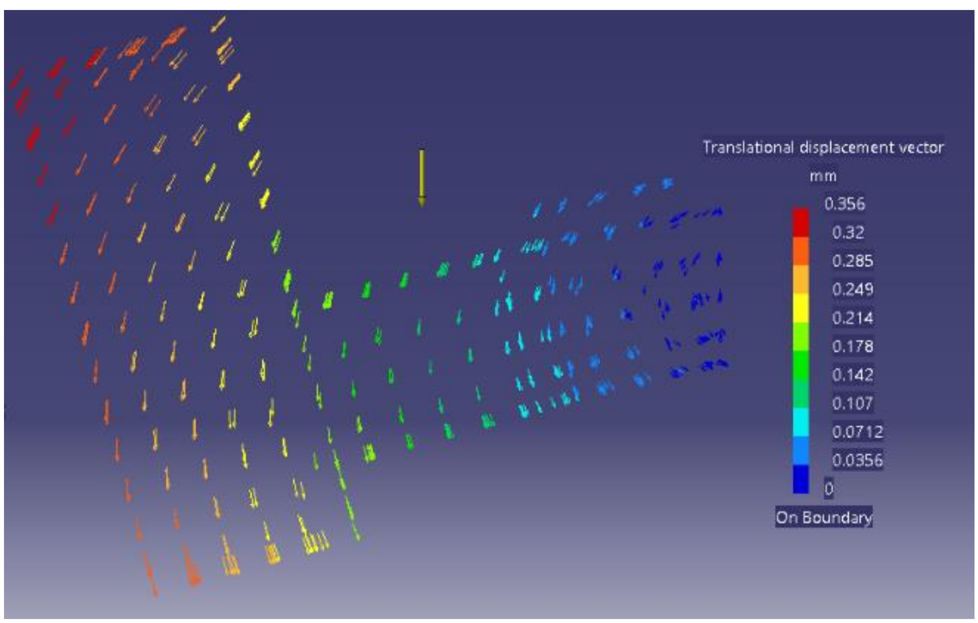


Figure 21: Translational displacement vector (Monel 600 analysis)

From all the figures of result shown for each type of material, a table is shown below summarizing the analysis done from the simulation.

Table 29: Summary of static analysis of the structure on four different materials

Material	Iron	Carbon steel	Stainless steel	Monel 600
Deformation	Similar deformation			
Max Von Mises stress value	$7.629x10^7Nm^2$	$7.623x10^7Nm^2$	$7.625x10^7Nm^2$	$7.621x10^7Nm^2$
Max Translational displacement vector value	1.05mm	0.351mm	0.382mm	0.356mm

A smaller stress value on the structure means that the structure is made of a stronger element material and thus receiving lesser stress from the load given. From the above table, it is seen that the Von Mises stress values are almost similar ranging from $7.621x10^7Nm^2$ to $7.629x10^7Nm^2$. Von Mises stress is considered to be safe haven for design engineers. Design will fail if and only if the stress value is more than the strength of the material itself. In this case of the simulation, the higher Von Mises stress value means that the material is not a good choice to be used for the building of the structure. Iron has the highest among the four choices of materials. Following iron are stainless steel, carbon steel and lastly Monel 600 in order. Even though the maximum Von Mises stress value of all the materials does not exceed the strength of each material, over time, the stresses on the parts will soon give away in the structure. This statement is further supported by the translational displacement vector generated by the simulation. The structural analysis shows the maximum translational displacement vector that each material will endure when the loads are applied. The values are range from 0.351mm to 1.05mm. The highest displacement seen; which is 1.05mm from the iron material shows that iron is a no-go material to be chosen as the material in building the structure. Comparing carbon steel and Monel 600, both materials have the better Von Mises stress value and lesser translational displacement. Now that from the technical part of understanding, the costing of each material should be put into consideration as well. Below is a short summary of the current market cost of each material.

Table 30: Cost of the suggested material to be used in the manufacturing of equipment

No	Material	Cost (USD/Kg)	Properties
1	Iron	0.5	- Soft and ductile - Malleable - Stress corrosion cracking - Rust in the present of moisture - Galvanic corrosion - Fatigue resistance
2	Carbon Steel	0.5	- Used as manufacture parts in machinery - Durable - Capable of withstanding shocks and vibration - More tough and elastic than mild steel - Stronger in compression than in tension
3	Stainless Steel	1.6	- Corrosion resistance - Sanitary quality - More durable than most sheet metals. - Inter-granular corrosion under intense heat 900 to 1500^{o}F - Sensitive to hydrochloric acid. - Pitting can occur - Expensive
4	Monel 600	3.0	- Good corrosion resistance - Stronger than steel - Extremely expensive

Iron and carbon steel are the cheapest as compared with stainless steel and Monel 600. However the strength of the material is more critical to be considered as the main factor of choice in building the structure. Even though Monel 600 is a stronger element as compared with the carbon steel, the price of Monel 600 is far too expensive at USD3.0/kg. From the simulation and comparing the cost of each material, the best option for the choice of material is the carbon steel.

4.4.5 Screw-on Bit Holder and Rock Specimen Holder

The screw-on bit holder is an equipment that will be joining the drilling bit and the hydraulic motor. This bit holder has two box ends. One side of the box will have a diameter that is according to the hydraulic motor output end and the other the box diameter according to the bit thread diameter used. The rock specimen holder on the other hand is also made up of similar material such as the screw-on bit holder. Selection of the material used in designing this rock specimen holder is similar to the process in coming to the final material used for the screw-on holder. This is because the material used is easier to get and able to be manufactured in-house. The design specifications are shown in the table below.

Table 31: Design specification of the rock specimen holder

Parameter	Specification
Base of holder	0.8m(L) x 0.5m(W)
Height of holder	0.22m
Clamping size	3inch – 6 inch diameter
Screw diameter	0.01m
Screw length	0.26m

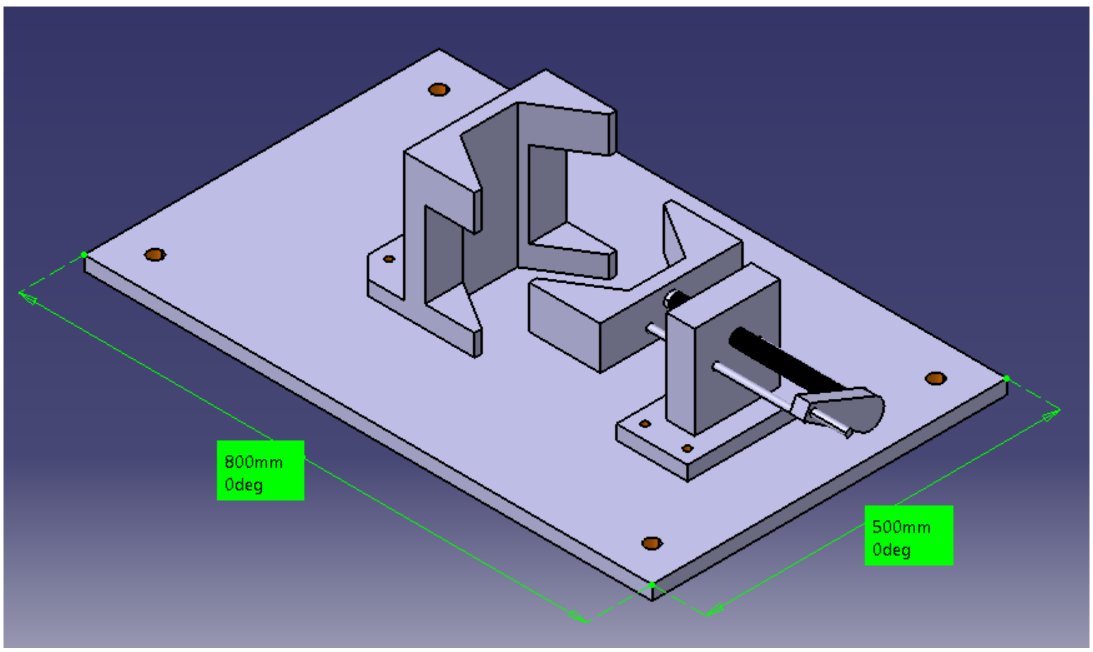


Figure 22: Rock Specimen Holder (Isometric View)

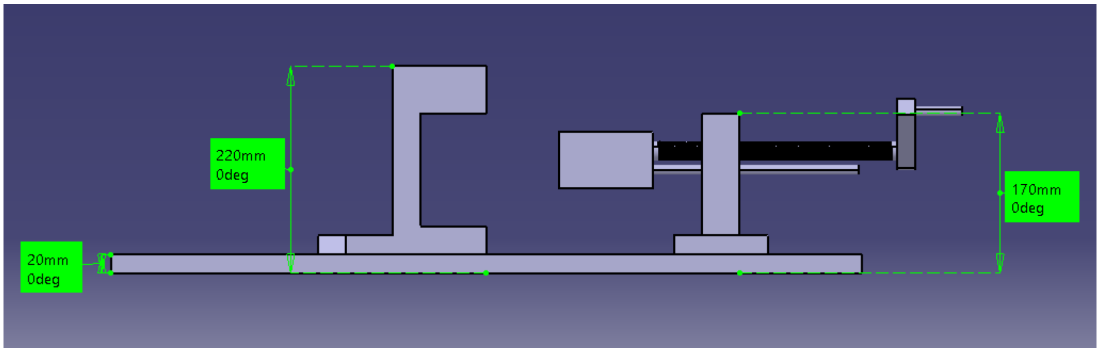


Figure 23: Rock Specimen Holder (Front View)

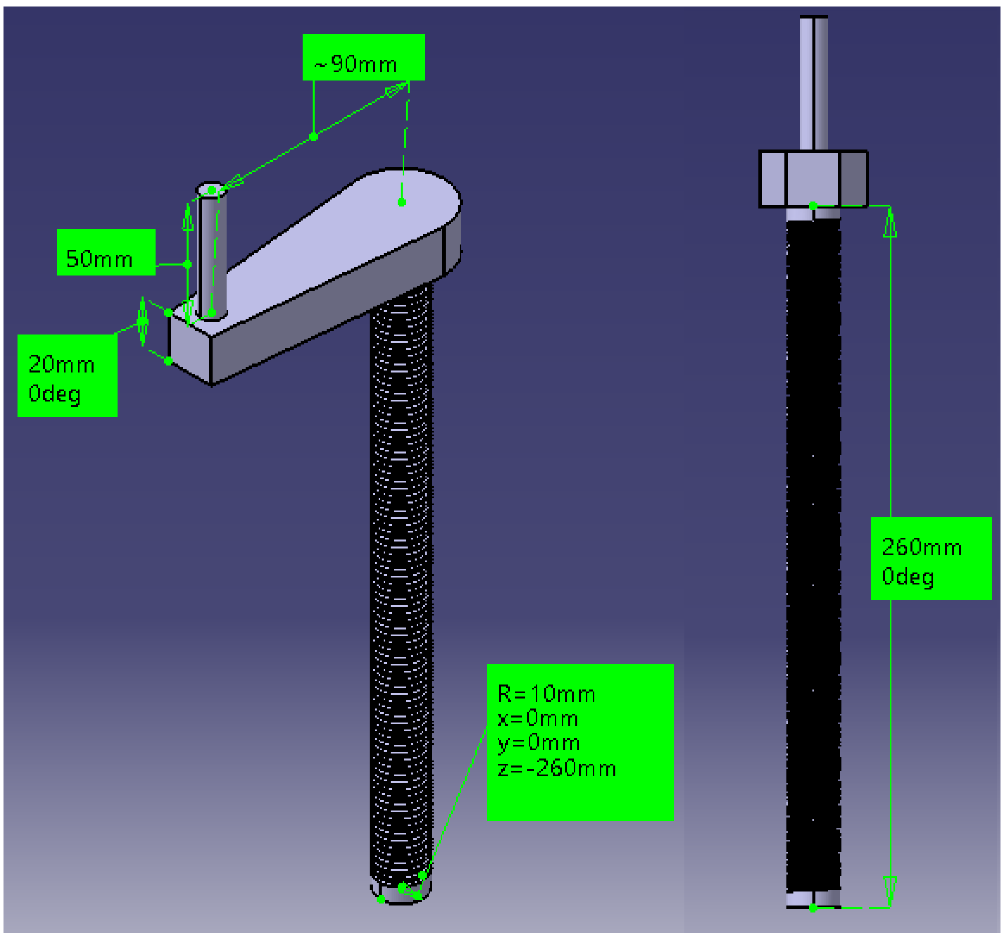


Figure 24: Screw handle (Isometric and front view)

Chapter 5

Conclusion

The oil and gas industry is an industry where the cost of operating is very important and all the companies would want to save cost. One of the factors that contributes to costly drilling operations is the drilling bit not performing at its best as there are occurrence of bit wear and also vibration. This brings up the matter of having a lab-scale drilling rig in order to run testing of bits and to assimilate the drilling conditions that are faced on the drilling rig within the laboratory itself. Thus the project of designing the lab-scale drilling test rig. Using the GO/NO-GO screening to identify the more feasible equipment before a series of decision making approach was used such as the weighted evaluation matrices and also the Analytical Hierarchy Process in order to help ease the selection process. The conceptual design was generated and then a thorough analysis of the design concept is done in order to select the best material used for the manufacturing of in-house equipment. Carbon steel was the final choice of material for the manufacturing of the test rig structure. The objective of the project was met as at the end of the project, a designed was generated and finite element analysis of the design structure was done. From the positive outcome of this project, a safe operating drilling test rig would be manufactured to be used in aiding drilling optimization of the drill bits in future researches.

Recommendation

As a recommendation, as this project has only three systems namely the rotary system, feeding system and also the clamping system; in the future work, the circulation system and also the control system should be integrated together with the current system generated. This is to fully have a laboratory scale drilling rig that resembles fully to what the oil and gas drilling rig platform has. Besides that, using the ANSYS CFD Fluent software is a plus point when running simulation that involves the circulation system as the circulation of drilling mud is very much important to the drilling operations. This is because the circulation system would then cool the drilling bit and also help in drilling performances.

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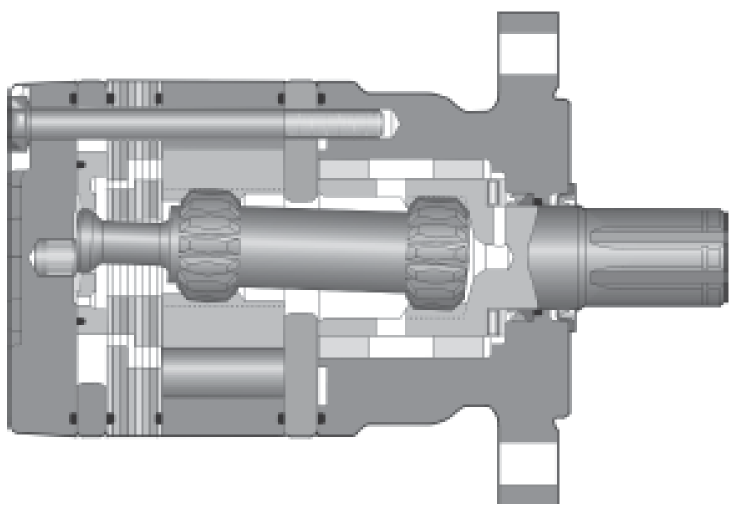
Appendices

Appendix 1 – TC Series Hydraulic Motor

	Cont	Int
15 Displacements **15 Schluckvolumen** **15 Cylindrée** **15 Despazamientos**		(2.2 - 24.0 in³/rev) **36 . . . 390 cm³/rev**
Maximum Pressure **Max. Druckgefalle** **Chaute de pression max.** **Presion Maxima**	(1250 psid) **. . .86 bar**	(1750 psid) **. . .121 bar**
Maximum Oil Flow **Schluckstrom** **Débit d'huile** **Caudal Maximo de Aceite**		(15 gpm) **. . . 57 lpm**
Maximum Speed **Drehzahl** **Vitesse de rotation** **Velocidad Maxima**		(902 rpm) **902 rpm**
Maximum Torque **Max Drehmoment** **Couple Maxi** **Torque Maximo**	(1905 lb in) **215.2 Nm**	(2709 lb in) **306.1 Nm**
Maximum Side Load **Seitenlast** **Charges latérales** **Carga Maxima Lateral**		(788 lb) **. . . 3505 N**

Big Performance In A Small Package

High Performance and long life in a reduced space envelope describe Parker's TC Series motors. High volume fluid flow continually washes across splines and seals to extend their life. Roller vanes and sealed commutation assure high volumetric efficiency and smooth low speed operation.



Appendix 2 – TG Series Hydraulic Motor

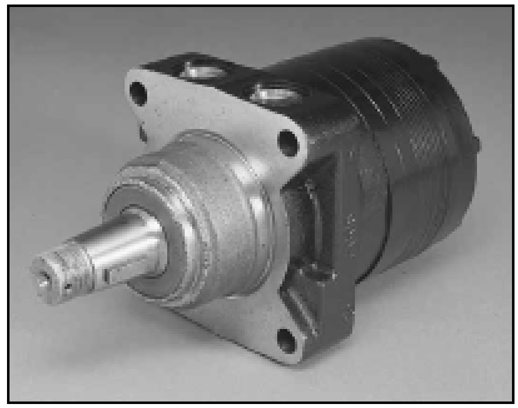
Technical Information /Technische Information / Segni/Informacion Tecnica

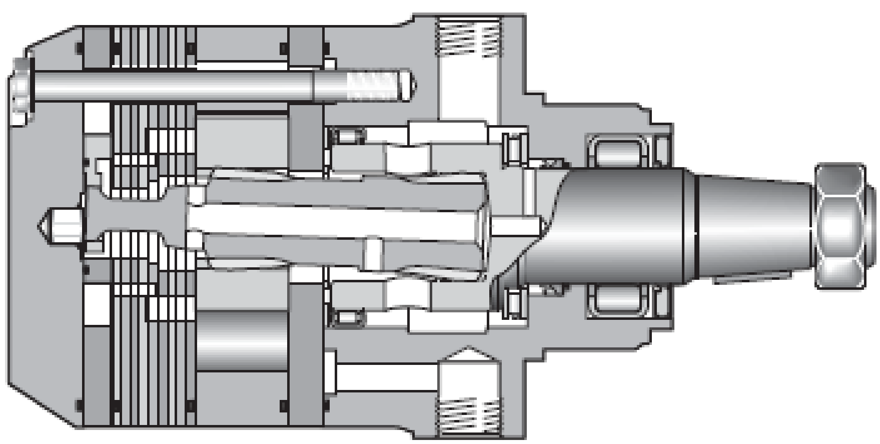
LSHT Torqmotors™ and Nichols™ Motors
TG Series / Serie / Série HY13-1590-009/US,EU

	Cont.	Int.
13 Displacements 13 Schluckvolumen 13 Cylindrée 13 Despazamientos		(8.6 to 58.5 in^3/rev) 141 . . . 959 cm^3/rev
Maximum Pressure Eingangsdruck Pression entrée Presion Maxima	(3000 psid) . . . 207 bar	(4000 psid) . . . 276 bar
Maximum Oil Flow Schluckstrom Débit d'huile Caudal Maximo de Aceite		(30 gpm) . . . 114 lpm
Maximum Speed Drehzahl Vitesse de rotation Velocidad Maxima		(660 rpm) 660 rpm
Maximum Torque MaxDrehmoment Couple Torque Maximo	(9,239 lb in) 1044 Nm	(12,636 lb in) 1428 Nm
Maximum Side Load at Key Seitenlast Charges latèrales Carga Maxima Lateral		(3597 lb) . . . 16000 N

Exceptional Strength and Durability in a High Performance Motor

The heart of Parker's TG Series powertrain, the torque link, is an extra heavy duty part that includes unique 60:40 spline geometry. Rugged construction throughout allows the transmission of over 13,000 lb-in of torque. The entire powertrain is continually washed in cool, high flow fluid to assure long life. Roller vanes and sealed commutator maintain high efficiency and provide smooth low speed performance.



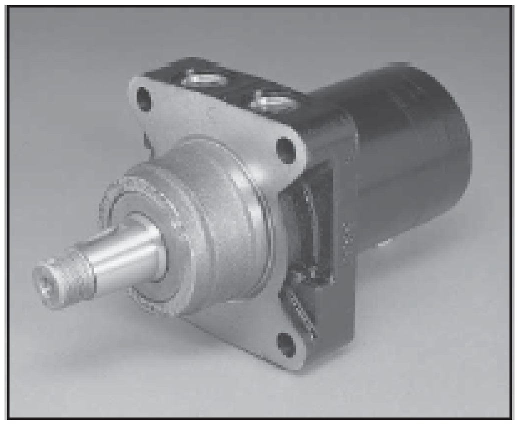


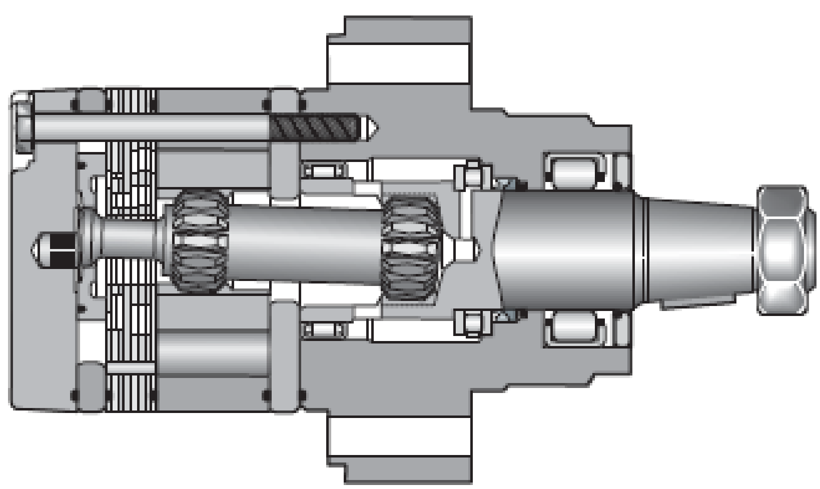
Appendix 3 – TJ Series Hydraulic Motor

14 Displacements 14 Schluckvolumen 14 Cylindrée 14 Despazamientos		(2.5 – 24.0 in³/rev) 41 . . . 390 cm³/rev
	Cont	Int
Maximum Pressure Eingangsdruck Pression entrée Presion Maxima	(2030 psid) . . .140 bar	(2750 psid) . . .190 bar
Maximum Oil Flow Schluckstrom Débit d'huile Caudal Maximo de Aceite		(20 gpm) . . . 75 lpm
Maximum Speed Drehzahl Vitisse de rotation Maxi Velocidad Maxima		(1024 rpm) 1024 rpm
	Cont	Int
Maximum Torque Max Drehmoment Couple Maxi Torque Maximo	(4139 lb in) 467 Nm	(5728 lb in) 648 Nm
Maximum Side Load at Key Seitenlast Charges latérales Carga Maxima Lateral		(3150 lb) . . . 14000 N

The Ultimate in Performance from a Medium Frame Motor

Parker's TJ Series motor provides all that could be expected of a general purpose motor and more. Unique 60:40 spline geometry provides drivetrain strength for severe applications. Roller vanes and sealed orbit commutation assure high volumetric efficiency and smooth slow speed operation. Cooling fluid flow across splines and seals mean long, trouble-free life.





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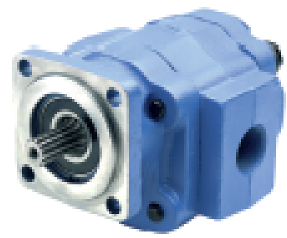
Appendix 4 – PERMCO 5000/5100 Series Hydraulic Motor

PERMCO

TECHNICAL SPECIFICATIONS

5000/5100 SERIES

Medium displacement roller bearing pump and motor



PUMP PERFORMANCE CHART [gpm]

GEAR WIDTH [in]

SPEED [rpm]	1/2	3/4	1	1 1/4	1 1/2	1 3/4	2	2 1/4	2 1/2	2 3/4	3
600	—	—	5.5	7.0	8.5	10.0	11.0	12.0	13.0	—	—
900	—	—	8.5	11.0	13.0	16.0	17.5	19.0	21.0	—	—
1000	—	—	9.5	12.0	14.5	17.5	19.5	21.0	23.5	—	—
1200	—	—	11.5	15.0	18.0	21.5	24.0	26.5	29.0	—	—
1500	—	—	15.0	19.0	23.0	27.0	30.5	33.5	37.5	—	—
1800	—	—	18.0	23.0	28.0	33.0	37.0	41.0	46.0	—	—
2100	—	—	31.0	37.0	32.5	38.5	43.5	48.0	54.0	—	—
2400	—	—	24.0	31.0	37.5	44.0	50.0	55.5	62.0	—	—
Max RPM	—	—	2400								
Displacement (in^3)	1.29	1.93	2.57	3.22	3.86	4.50	5.15	5.79	6.43	—	—
Displacement (cc)	21.10	31.60	42.10	52.80	63.30	73.70	84.40	94.90	105.40	—	—
Max Operating PSI	3000					2500					

SPECIFICATIONS

Series	Type	Frame Size	Displacement	Max RPM	GPM @ 1000RPM	Max PSI
5000/ 5100	Bearing	Medium	1.28-6.43	2400	9.5-23.5	3000

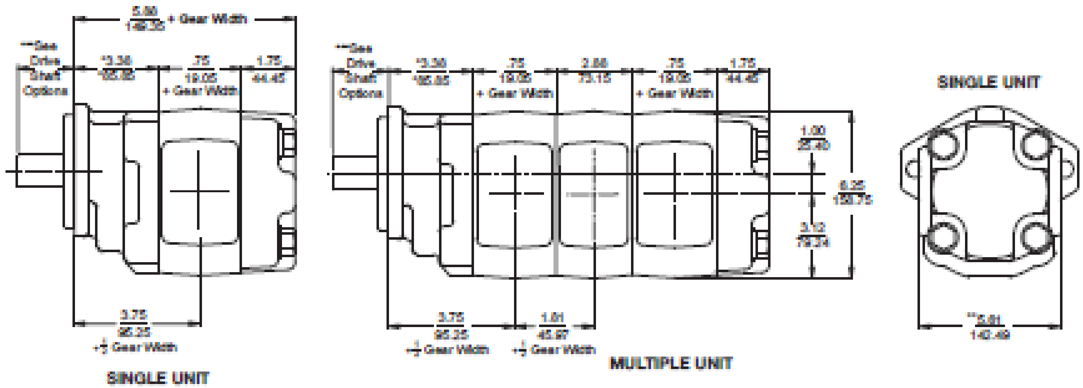
5000/5100 SERIES

MOTOR PERFORMANCE CHART

GEAR WIDTH [in] — M5000/ M5100 @ 2000 PSI

SPEED [rpm]	1			1 1/2			2			2 1/2		
	Input (GPM)	Output Torque (In-lb)	Output (HP)	Input (GPM)	Output Torque (In-lb)	Output (HP)	Input (GPM)	Output Torque (In-lb)	Output (GPM)	Input (GPM)	Output Torque (In-lb)	Output (GPM)
800	11	730	9	16	1140	14	21.5	1530	18.5	26.5	1900	24
1000	13.5	725	11.5	19.5	1130	18	26	1410	24	32	1885	30
1200	16	720	13.5	23	1120	21	31	1495	28	37.5	1870	35.5
1800	20.5	710	17.5	30.5	1100	27	40.5	1470	37	50	1820	45
2000	25.5	670	21	38	1040	32.5	50	1410	44.5	62	1740	55

DIMENSIONAL DATA



DISCLAIMER Consult your Permco Representative or the factory for operation below 600 or above 2400 RPM and temperatures above 180° F. Oil Viscosity: 150 SUS (32.1 cSt.) at 100° F (37.8° C) | Oil Temperature: 150° F (65.5° C)

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Version 1.0 : Permco 2012

Appendix 5 – Yuken AC Servo Motor Driven Hydraulic Pump

YUKEN

AC Servo Motor Driven Hydraulic Pump Control System

Intelligent Hydraulic Servo Drive Pack

The IH (intelligent hydraulic) servo drive pack is a compact energy-saving and low-noise hydraulic device which is combined as one with the AC servo motor, piston pump, reservoir and hydraulic control circuit. This combination can control the number of revolutions of the servo motor and adjust the discharge and pressure of the pump. This device can be combined with the sensor – equipped cylinder and dedicated controller to facilitate the configuration of a position, speed and pressure control system.

- **Energy Saving**
  The operation at the number of revolutions meeting the machine requirements (flow rate and pressure) reduces useless power losses and provides energy savings.
- **Low Noise**
  During pressure control, the pump rotation compensating for the internal leakage of oil pressure provides low revolutions with almost no noise.
  During flow control, the number of revolutions meeting the machine requirements ensures lower noise generation than conventional devices.
- **Compactness**
  A substantial reduction in heat generation enables the operation with a minimum amount of fluid oil for cylinder operation in addition something extra oil. This results in a combination of the servo motor, piston pump, reservoir and hydraulic control circuit in one, providing energy savings.
  Incorporation into an integral part of the machine is also possible.
- **Digital Control**
  Software control of the dedicated controller allows a system to have a great deal of versatility because of making use of a CPU. Digital control parameter setting facilitates to operate the system and its maintenance, furthermore the analog input/output ports provide as standard for user interface.

Specifications

Model Numbers	Geometric Displacement of Pump cm^3/rev (cu. in./rev)	Maximum Shaft Speed r/min	Thrust Output and Cylinder bore	Reservoir Capacity cm^3 (cu. in.)	Oil Level Variations cm^3 (cu. in.)
YSD1–●–09 YSD1–●–13	6 (.366) 10 (.610)	2000 Note) It may vary according to AC servo motor output and operating pressure.	20 – 30 kN (45 – 67.4 lbs.) Cyl. Bore 63 mm (2.48 in.)	2500 (152.6)	1500 (91.5)
YSD2–●–18 YSD2–●–29 YSD2–●–44	6 (.366) 10 (.610) 16 (.976)		50 – 60 kN (112 – 135 lbs.) Cyl. Bore 80 mm (3.15 in.)	4200 (256.3)	2500 (152.6)
YSD3–●–55 YSD3–●–75	10 (.610) 16 (.976) 30 (1.831)		100 kN (225 lbs.) Cyl. Bore 100 mm (3.94 in.)	5800 (353.9)	3500 (213.6)

AC Servo Motor Output and Operating Pressure (for reference)

Continuous Operating / Short Time Operating

Model Numbers	AC Servo Motor Output kW (HP)	AC Servo Motor Rated Torque Nm (in. lbs.)	Geometric Displacement cm^3/rev (cu. in./rev)	Max. Operating Pres. MPa (PSI) 3.5 (510)	7.0 (1020)	10.5 (1525)	14.0 (2030)	17.5 (2540)	21.0 (3.50)
YSD1–✱–09	0.85 (1.14)	5.39 (44.7)	6 (.366)						
			10 (.610)						
YSD1–✱–13	1.3 (1.74)	8.34 (73.8)	6 (.366)						
			10 (.610)						
YSD2–✱–18	1.8 (2.4)	11.5 (101.8)	6 (.366)						
			10 (.610)						
			16 (.976)						
YSD2–✱–29	2.9 (3.9)	18.6 (165)	10 (.610)						
			16 (.976)						
YSD2–✱–44	4.4 (5.9)	28.4 (251)	10 (.610)						
			16 (.976)						
YSD3–✱–55	5.5 (7.4)	35 (310)	16 (.976)						
			30 (1.831)						
YSD3–✱–75	7.5 (10.1)	48 (425)	16 (.976)						
			30 (1.831)						

Note: The above table is guidance for model selection. It is required to take operating condition of hydraulic power unit such as cycle time in consideration when selecting the AC servo motor. Please contact us for more details.

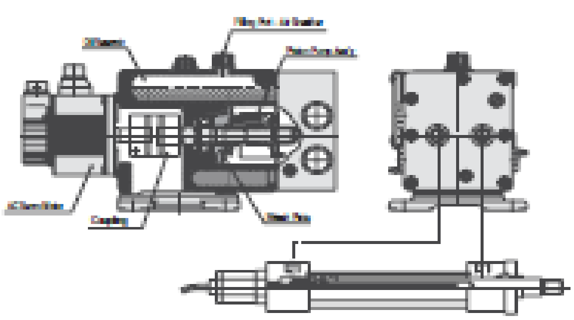
Model Number Designation

YSD3	-F	-55	A	55	-16	-H	H	-B	A	B	H	-20	*
Series No.	Mfg. Type	Servo Motor Output	Direction of Servo Motor Connection	Servo Pack	Geometric Displacement of Pump cm³/rev (cu. in./rev)	Relief Valve Setting Pres. MPa (PSI)	Location of Pressure Sensor	Location of Counter-balance Valve	Setting Pres. of Head Side Counter-balance Valve MPa (PSI)	Setting Pres. of Rod Side Counter-balance Valve MPa (PSI)	Location of Shut-off Valve	Design Number	Design Std.
YSD1		N1: Without Servo Motor (for 0.85 kW) N2: Without Servo Motor (for 1.3 kW) 09: 0.85 kW (1.14 HP) 13: 1.3 kW (1.74 HP)		N: Without Servo Pack 09: 0.85 kW (1.14 HP) 13: 1.3 kW (1.74 HP)	6: 6 (.366) 10: 10 (.610)	B: 9.5 (1380) C: 18.5 (2680)		—	—	—	—	10	
YSD2	F: Flange Mtg. B: Foot Mtg.	N: Without Servo Motor 18: 1.8 kW (2.4 HP) 29: 2.9 kW (3.9 HP) 44: 4.4 kW (5.9 HP)	(Viewed from the Motor End) A: Upwards B: Downwards R: Right L: Left None: Without Servo Motor	N: Without Servo Pack 18: 1.8 kW (2.4 HP) 29: 2.9 kW (3.9 HP) 44: 4.4 kW (5.9 HP)	6: 6 (.366) 10: 10 (.610) 16: 16 (.976)	B: 9.5 (1380) C: 18.5 (2680) H: 23.5 (3410)	H: Head Side R: Rod Side B: Both Sides None: Without pressure Sensor	H: Head Side R: Rod Side B: Both Sides None: Without Counter-balance Valve	B: * - 7 (* - 1020) None: Without Head Side Counter-balance Valve	B: * - 7 (* - 1020) None: Without Rod Side Counter-balance Valve	H: Head Side R: Rod Side B: Both Sides None: Without Shut-off Valve	20	Refer to ★
YSD3		N: Without Servo Motor 55: 5.5 kW (7.4 HP) 75: 7.5 kW (10.1 HP)		N: Without Servo Pack 55: 5.5 kW (7.4 HP) 75: 7.5 kW (10.1 HP)	10: 10 (.610) 16: 16 (.976) 30: 30 (1.831)				N: * - 1.8 (* - 260) A: 1.8 - 3.5 (260 - 510) B: 3.5 - 7 (510 - 1020) None: Without Head Side Counter-balance Valve	N: * - 1.8 (* - 260) A: 1.8 - 3.5 (260 - 510) B: 3.5 - 7 (510 - 1020) None: Without Rod Side Counter-balance Valve		20	

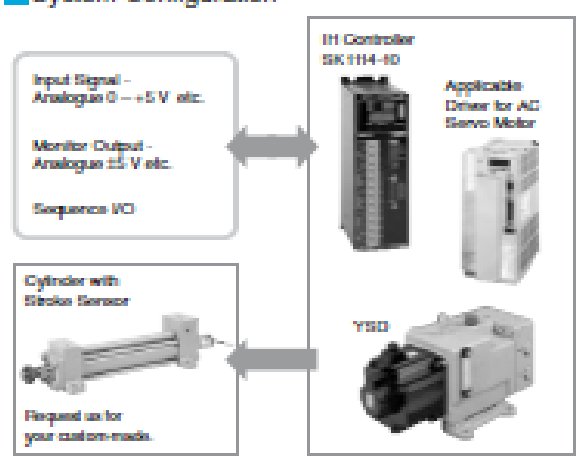
★. Design Standards: None .... Japanese Standard "JIS"
80 .... European Design Standard
950 .... N. American Design Standard

Structure

The IH Servo Drive Pack pump is a bidirectional revolution piston pump which offers high performance in a wide range of very low to high revolutions. The hydraulic control circuit simply consists of safety valves and self priming valve, without a control valve in the pump discharge line and the series line between cylinders. The reservoir is made compact by using space around the pump. With the oil supply port of hydraulic fluid doubling as an air breather and the side-mounted oil level gauge, the pump is well equipped as a hydraulic driving force.

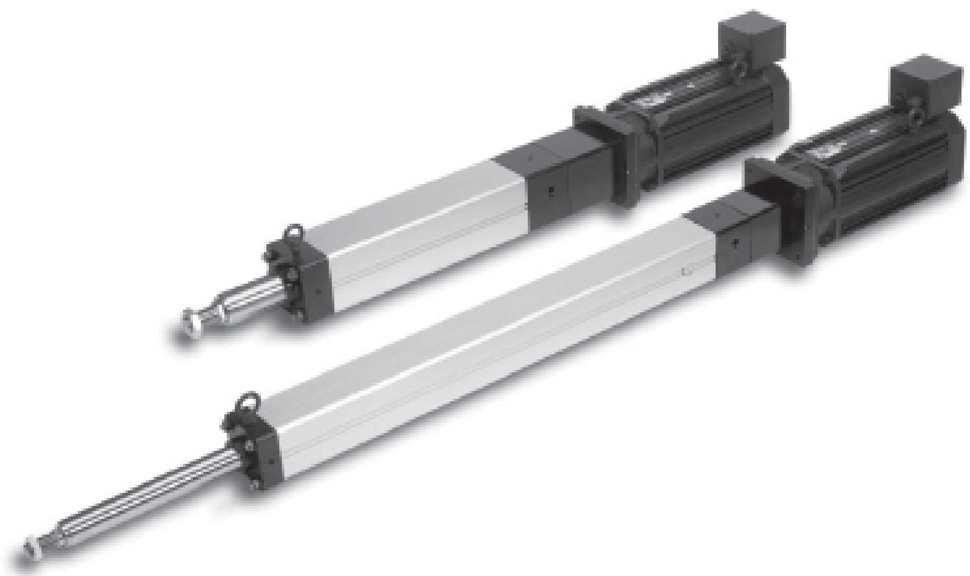


System Configuration



Consult Yuken when detailed material such as dimensions figures is required.

Appendix 6 – ETR Series Electric Cylinder



Electric Cylinder Feature Analysis

Feature	Advantage	Benefit
Ground and polished precision stainless steel rod	Resists corrosion	Longer life
Dual direction angular contact or tapered roller bearings to support back end of screw	Ability to handle both radial and thrust loads generated by screw	Longer screw life, longer bearing life
High load Torlon anti-rotate bearings	Eliminates rod play and noise, rigidly supports the screw	Longer screw life, smooth operation, greater accuracy.
Enclosed tie rod design	Structual strength for extrusion body	Longer life
Combination lip seal and wiper seal on rod	Keeps grease in cylinder, keeps contamination out	Longer screw life, less maintenance required
Global drop-in position sensor provides sensing target for cylinder mounted switches	Low profile to the extrusion body	Reduces cost, simplifies design Low profile
Oil bath lubrication option on roller screw (horizontal mounting only)	Higher velocity than grease lubrication	Cooler running conditions
External lubrication ports on cylinder body and rear end caps	Ease of maintenance process	Maintain with minimal downtime
Substantial bearing support for front end of roller screw	Screw support eliminates whipping, vibration run out.	Longer screw life, greater position accuracy

Performance Overview

	ETR50	ETR80	ETR100	ETR125
Max Thrust, kN (lb)	6.5 (1460)	18 (4050)	45 (10,120)	100 (22,480)
Max Speed - Oil Cooled, mm/sec (in/sec)	1244 (49)	933 (37)	1296 (51)	972 (38)
Max Speed - Grease Cooled, mm/sec (in/sec)	933 (37)	700 (28)	972 (38)	729 (29)
Max Acceleration* , mm/sec^2 (in/sec^2)	8,912 (351)	11,140 (439)	22,280 (877)	22,280 (877)
Max Body Inertia, cm^4 (in^4)	1107 (26.6)	450 (10.8)	187 (4.49)	45 (1.08)
Max Stroke, mm (in)	800 (31.5)	800 (31.5)	1000 (39.4)	1000 (39.4)

*Acceleration is dependent on the drive motor.

System Characteristics

Bidirectional repeatability - Inline, mm (in)	±0.025 (±0.001)
Bidirectional repeatability - Parallel, mm (in)	±0.15 (±0.006)
Lead accuracy per 300mm of length, mm (in)	±0 .012 (±0.0005)
Straightness of extrusion per 300mm of length, mm (in)	±0.20 (±0.008)

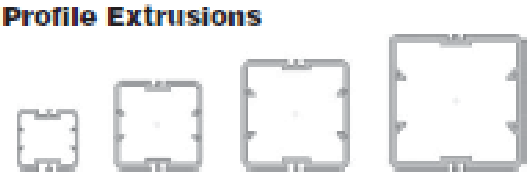
Screw and Drive Properties

Size	Lead (mm)	Efficiency	Pulley Diameter (mm)
50	5	0.89	44.6
	8	0.9	44.6
80	5	0.87	71.3
	10	0.89	71.3
100	5	0.84	86.6
	10	0.88	86.6
	20	0.9	86.6
125	5	0.82	101.9
	10	0.87	101.9
	20	0.89	101.9

Operation Temperature Range

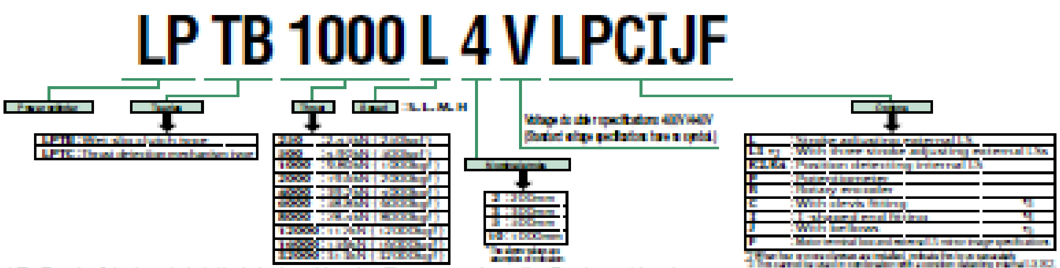
0°C to 60°C (32°F to 140°F)

Profile Extrusions


ETR50 ETR80 ETR100 ETR125

Appendix 7 – Tsubaki T Series Power Cylinder

Model No. designation



* The Trunnion fitting is not included in the body model number. Please separately specify a Trunnion model number.
* Manual operating handles are also available.

Standard model list

Power cylinder model			Rated thrust N	Rated thrust (kgf)	Nominal speed 50/60Hz mm/s	Motor output kW	Rod movement per one turn of manual shaft mm	Rod rotating force N·m	Rod rotating force (kgf·m)	Nominal stroke mm	Brake specifications
LPTB LPTC	250	S L M H	2.45k	250	12.5/15 25/30 50/60 100/120	0.1 0.1 0.2 0.4	2.0 1.0 2.0 4.0	2.65	0.27	200, 300, 400 500, 600	● DC brake ● Brake external wiring is available
LPTB LPTC	500	S L M H	4.90k	500	12.5/15 25/30 50/60 100/120	0.1 0.2 0.4 0.75	2.0 1.0 2.0 3.9	5.29	0.54	200, 300, 400 500, 600, 800	
LPTB LPTC	1000	S L M H	9.80k (7.84k)	1000 (800)	12.5/15 25/30 50/60 100/120	0.2 0.4 0.75 1.5	2.0 1.0 2.0 4.0	14.7	1.50	200, 300, 400 500, 600, 800 ※1000 [illegible]	
LPTB LPTC	2000	S L M H	19.6k (15.6k) (12.2k)	2000 (1600) (1250)	12.5/15 25/30 50/60 75/90	0.4 0.75 1.5 2.2	2.0 1.0 2.0 3.0	35.3	3.60	200, 300, 400 500, 600, 800 ※1000 [illegible] ※1200 [illegible]	
LPTB LPTC	4000	S L M H	39.2k (33.3k)	4000 (3400)	9/11 25/30 35/42 60/72	0.75 1.5 2.2 3.7	1.4 1.0 1.4 2.4	83.3	8.50	200, 300, 400 500, 600, 800 1000, 1200, ※1500 [illegible]	
LPTB LPTC	6000	S L M H	58.8k	6000	6.3/7.6 17.5/21 25/30 42/50	0.75 1.5 2.2 3.7	1.0 0.7 1.0 1.7	124	12.7	500 1000 1500	
LPTB LPTC	8000	S L M H	78.4k	8000	10/12 20/24 30/36 43/52	1.5 2.2 3.7 5.5	1.2 0.8 1.2 1.7	222	22.7	500 1000 1500	
LPTB LPTC	12000	L M H	117k	12000	10/12 18/22 30/36	2.2 3.7 5.5	1.2 2.2 1.2	333	34.0	500 1000 1500 2000	
LPTB LPTC	16000	L M H	156k	16000	14.5/17.5 20/24 31/37	3.7 5.5 7.5	2.9 3.2 3.7	666	68.0	500 1000 1500 2000	
LPTB LPTC	32000	L M H	313k	32000	10/12 15/18 20/24	5.5 7.5 11	0.4 0.6 0.8	1.33k	136	500 1000 1500 2000	

Note) The numerical value in parentheses on rated thrust is for the long stroke type.

1) The rated thrust is limited for the stroke marked with an*.
2) The speeds indicate a value at the motor synchronized rotating speed.

Motor specifications

Model	Totally enclosed self cooling type with brake
Output	Refer to Standard model dimensions list
Number of poles	4 poles
Voltage	3φ 200V/200V/220V
Frequency	50Hz/60Hz/60Hz
Heat resistance class	E
Time rating	S2 30min.
Protection method	Totally enclosed outdoor type (IP55)

1) 400/440V, different voltage specifications other than the above voltages are also available.
2) For motor current value and brake current value, refer to page 87.

Painting color

TSUBAKI olive gray (Munsell 5GY6/0.5 or approximate color)

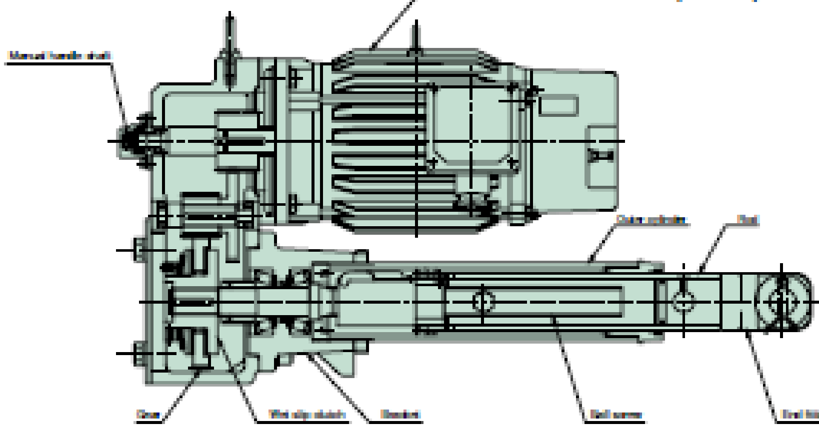
Standard use environment

Model \ Environment	Ambient temperature	Relative humidity	Input vibration value	Installation altitude	Atmosphere
Outdoor type	−15°C ~ 40°C	85% or less (no condensation)	1G or less	1000m or lower above sea level	Normally outdoors

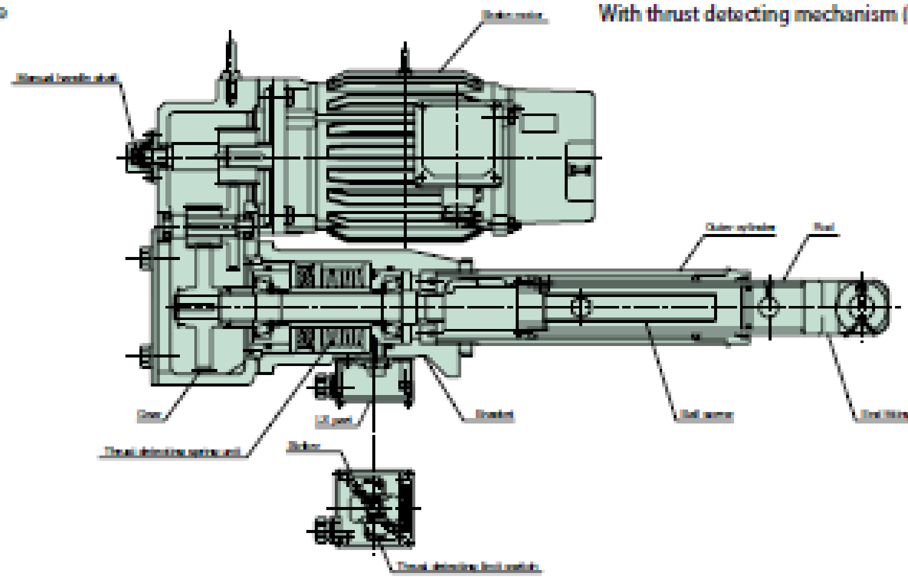
1) Cylinders with bellows are recommended in an excessively dusty location.
2) Special painting is available for locations exposed to sea breeze and salt. Consult us.
3) All models are totally enclosed structures so that they can be used normally outdoors, however, under adverse conditions exposed to constant water and steam etc., and snow accumulation, although they are an outdoors type, an appropriate cover is required. When using at 40°C or higher, always protect with a heat insulating cover, etc. Never use in a flammable atmosphere, otherwise it may cause an explosion and fire. In addition, avoid using it in a location where vibration or shock exceeding 1G is applied.

Structure

TB type — With wet slip clutch protection device (Basic type)



TC type — With thrust detecting mechanism (Basic type)



* The structure slightly varies depending on the model.

Brake motor — This motor adopts a deenergization operation type (spring close type), and the brake is applied while the cylinder stops. This brake action holds load while the power cylinder stops and reduces coasting during stoppage, and serves the purpose of increasing stop accuracy.
All of the brake motors adopt outdoor types.

Reduction part — The reduction part adopts a combination of a helical gear on the high speed side and a spur gear on the low speed side.
The lubrication method is grease bath type, and has a quiet operating specification. Furthermore, a manual handle shaft is provided, and the structure of the speed reducer facilitates operation at power failure and adjustment for installation.
As options, various position detecting devices can be installed.

Actuation part — The actuation part is provided with a ball screw and nut which converts a rotating force into linear motion. Further, external limit switches for stroke adjustment can be mounted.
A high precision ball screw and nut have advantages such as high transmission efficiency, less wear, long life and easy lubrication.
The external limit switches for stroke adjustment are structured to freely adjust the stroke and endure outdoor use. The bellows are excellent in weatherproofing, and the stroke does not change even if the bellows are mounted.
The seal for the rod also endures outdoor use.