Design Study and Analysis of Water Hydraulic High Torque Low Speed Motor

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Abstract **- In nuclear reactors, process as well as power water hydraulics is extensively used to avoid intermixing of oils with water which is used as coolant and moderator. A Fuelling Machine (*FM*) is used for on-power refueling of Pressurized Heavy Water Reactor (*PHWR*) and Advanced Heavy Water Reactor (*AHWR*). Many mechanisms of *FM* are operated under water environment to handle the fresh as well as used fuel. Use of Water Hydraulic (*WH*) actuators is preferred to actuate these mechanisms. It is desirable to use water hydraulic direct drives like High Torque Low Speed (*HTLS*) rather than using high speed motors with mechanical multipliers like gearbox, working inside the water environment. Mechanical multipliers avoided as they are prone to tribological problems like insufficient lubrication, high wear rate and friction, corrosion etc. under water environment. Water Hydraulic *HTLS* motors are not available in market, hence there is need to develop it indigenously. *WH* motor with radial piston configuration is one of the promising options for HTLS motor since in this design, as it has less number of moving parts and less dynamic sealing locations. This paper discusses comparison of various design configurations of hydraulic motor, problems associated with design of water hydraulic components and engineering solutions to overcome the same, theoretical analysis of radial piston *HTLS* motor.**

Index Terms **- Water Hydraulics, Radial Piston Motor, High Torque Low Speed (*HTLS*)**

I. INTRODUCTION

Nuclear reactors use water/heavy water as moderator and coolant. Very high purity of water is maintained in the reactor and intermixing of any other fluid/material is not allowed. A Fuelling Machine (*FM*) is used for on-power refueling of Pressurized Heavy Water Reactor (*PHWR*) and Advanced Heavy Water Reactor (*AHWR*). Many mechanisms of *FM* are operated under water environment to handle the fresh as well as used fuel. Water hydraulics is extensively used for actuators of mechanisms of *FM* to avoid intermixing of oils with water. Motors are used as actuators for many mechanisms of *FM*. Use high speed motors with mechanical multipliers like gearbox, operating inside the water environment, are prone to tribological problems like insufficient lubrication, high wear rate, corrosion, high friction etc. Hence it is desirable to use direct drives like High Torque Low Speed (*HTLS*) motor. *WH HTLS* motors are not readily available in international market. Hence, there is need to indigenously develop water hydraulic *HTLS* motors.

II. PROBLEMS OCCURRED IN WATER HYDRAULICS AND THERE REMEDIES

The problems associated with the water hydraulics are as follows [6]-

1. Lower viscosity of water as compared leads to higher leakages through available clearances. This leads to lower hydraulic efficiency of the pumps and motors.
2. Water is corrosive in nature.
3. Pure water does not contain constituents similar to those in mineral oils, which reduce static friction between moving components and reduce their wear rate when operating in rubbing contact. It is less effective in generating films between components, which operate with relative movement. If conventional metal components are used throughout, problem can be expected to arise from static friction and also from high wear rate and possible risk of component scuffing.
4. Water has high vapour pressure as compared to mineral oils. This makes water hydraulic components more susceptible to cavitation.
5. As water is very corrosive in nature, susceptible to cavitation, plus high velocity at control orifices cause high erosion-corrosion problem and wear of orifice will be fast. This phenomenon is called wire drawing.

The solutions for these problems are-

1. Material selection is a major factor for water hydraulic components. Stainless steels are used as material of construction for all the components.
2. Non-metallic materials like ceramics and polymers like PEEK are used as of bearing materials.
3. Special coatings [7] and surface treatments are carried out on moving parts to avoid seizing and scuffing of components.
4. The moving surfaces would also have to be made of extremely hard materials, with very smooth finishes.
5. Very low clearances are maintained between mating parts.
6. The bearing area of moving parts and load carrying components are over designed to reduce contact pressure since no film is being made by water at mating parts.

III. Types of Hydraulic Motors

HTLS motors have wide variety of designs so that direct comparison of performance between two types is virtually impossible. Instead, here are some important points about four of the main motors are discussed:

1. Gear Motor: A gear motor consists of two gears, the driven gear attached to the output shaft by using key and the idler gear. High pressure fluid is ported into one side of the gears then the fluid flows around the periphery of the gears between the gear tips and the wall housings where it forces the gears to rotate and exits through the opposite side of the motor.The gears then mesh and not allowing the oil from the outlet side to flow back to the inlet side. In this way the torque is generated [1]. Gear motors are very economical but it has lower volumetric efficiencies due to higher leakage rates. These motors are best suited only for low pressure applications.
2. Vane motors: These motors are positive displacement type common traditional hydraulic vane motors, in which hydraulic pressure act on a series of extended vanes. These vanes ride a ring cam and slide in and out of rotor slots and develop an output torque at its shaft [2]. The vanes form sealed chambers with the help of compression springs due to this which carry fluid from an inlet to an outlet. *HTLS* vane motors are radially unbalanced and continuous sliding of vanes on ring are prone to produce friction problems which affects on their operating life [1]. These motors have lower volumetric efficiency at slow speeds and poor starting characteristics due to large number of leakage paths.
3. Rolling Vane motors: In this type of motor the rolling vanes function as timing valves, they sequencing the fluid flow to ensure high pressure against trailing surfaces and low pressure against leading surfaces. Instead of direct contact between the stator and rotor, roller vanes are incorporated to form the displacement chambers. The roller vanes reduce wear and enabled the motor to be used in closed-loop, high-pressure hydrostatic circuits as direct-mounted wheel drives. This type configuration offers a nearly constant volumetric efficiency at all speeds but these motors have a limited displacement range and same as vane motors, it cannot tolerate cavitation effect.
4. Piston Motors: Piston type motors are the most commonly used in hydraulic systems. They are basically the same as hydraulic pumps except they are used to convert hydraulic energy into mechanical (rotary) energy. The most commonly used hydraulic motor is the fixed-displacement piston type. There are several different designs that fall under this category.
   i. Axial Piston motor: It develop torque through a reaction to pressure on reciprocating pistons. These motors have excellent high speed capabilities, but they are limited at low operating speeds and good volumetric efficiencies, especially at lower pressures [1].
   ii. Radial Piston motors: Radial piston motors have a large displacement range [3]. From the different types of Radial piston motor like Crankshaft type, Multi-lobe type motors, Cam type motor, Inverted eccentric type motor is most efficient motor in which pistons in radial arrangements are moved by eccentric drives which are similar to crankshaft arrangements though here pistons are not connecting physically to its drive but maintaining the contact through by spring force and it possesses a high leakage resistant characteristics. Hence, this type motor has good volumetric efficiency through the entire speed range. Mechanical efficiency of this type is more as compared to cam type radial piston motor since the number of moving components in inverted eccentric type are less than cam type due to this friction and wear is less. This type motor has a high starting torque and is very efficient in the medium to high displacement range. Hence, *WH* motor with radial piston configuration is one of the promising options for *HTLS* motor.

IV. Mathematical Modelling

In Radial piston motor, the force generated on the piston due to pressurized fluid is not continuous. For particular lap of angle the piston is connected to the pressurised port and for some period of angle it is closed and after that connects to outlet port. Similarly the spring force acting on piston is also changes due to variation of deflection of spring which depends on the stroke variation of piston. Thus the evaluation of exact torque generated by motor for particular pressure of fluid is essential to analyse the working of motor. Matlab-Simulink is used to carry out the analysis. Simulink is the data flow graphical programming language tool for modelling, simulating and analysing multi-domain dynamic systems and it is one of the best option to evaluate total torque produced by the motor.

Mathematical model of the Radial Piston motor is developed. The following assumptions were made in analysis:

1. Pressure losses in internal flow paths are negligible.
2. Vertical piston position is the reference to measure the angle of rotation of shaft.
3. Supplied water flow rate is constant throughout the cycle.
4. Shaft rotation in clockwise direction.
5. Water is assumed to be incompressible fluid.

i. Torque Calculations

A 5 piston Radial Piston Motor has been considered for theoretical analysis. Various forces acting on the shaft are:

a) Force Developed by pressure act on piston is as shown in fig.1:

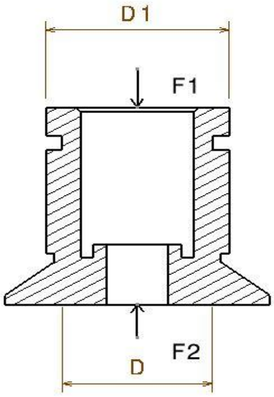

Figure1: Free Body Diagram for Piston

P = Fluid pressure = 10e6 N/m^2

D_1 = Diameter of piston = 38e-3 m

D = Mean diameter of bottom surface of piston = 33e-3 m

$A_1 = \pi D1^2/4 = 1134.11e\text{-}6\ m^2$

$A_2 = \pi D^2/4 = 855.3e\text{-}6 m^2$

Net Pressure Force acting on piston (F_p), $F_p = P\times(A_1 - A_2)$

b) Spring force (F_s):

X_0 = Maximum deflection of spring (m)

K = Stiffness of spring (N/m)

θ = Angle of rotation made by eccentric line w.r.t vertical axis (degree)

E = Maximum Eccentricity of shaft (m)

Force is varying as the deflection of spring changes w.r.t. shaft rotation therefore force is given by

$$F_s = K\times [X_0 - (E - E\cos(\theta))]$$

Torque produced by respective pistons is given as

$$T_1 = (F + F_s) \times E \sin(\theta)$$

$$T_2 = (F + F_s) \times E \sin(\theta + 72^0)$$

$$T_3 = (F + F_s) \times E \sin(\theta + 144^0)$$

$$T_4 = (F + F_s) \times E \sin(\theta + 216^0)$$

$$T_5 = (F + F_s) \times E \sin(\theta + 288^0)$$

Hence, Total Torque (T) can be calculated by

$$T = T_1 + T_2 + T_3 + T_4 + T_5$$

The variation of torque at various angular positions of shaft are calculated and shown in Fig-2.

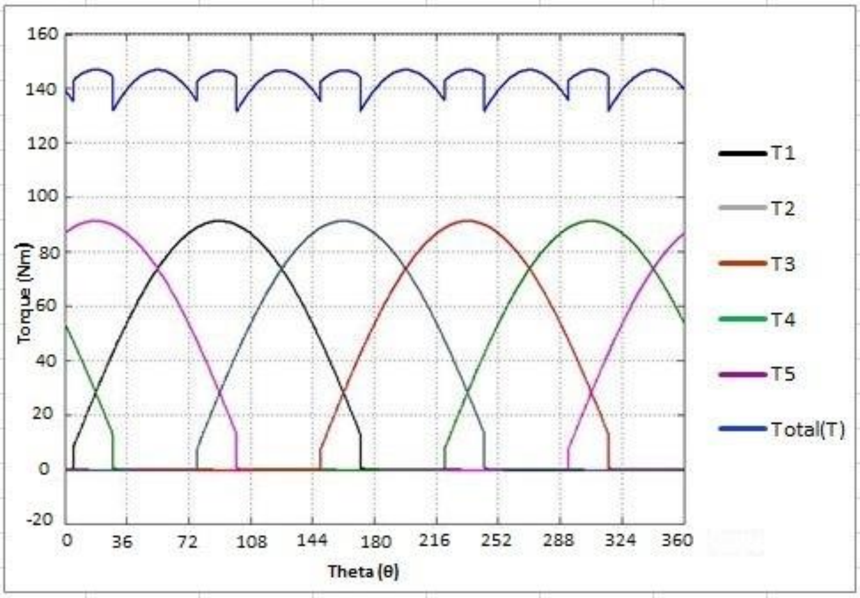

Figure 2: Torque generated by each Piston and total Torque

ii. Torque Calculation By Considering Friction

In this motor, the five pistons are continuously in contact with the flat surface of pentagonal nut. When shaft starts rotation, the pentagonal nut on shaft moves in a wobbling motion because of eccentricity of shaft and due to this the pistons rested on it. The pistons slide in particular range on the surface of bearing pad which is perpendicular to axis of piston. Friction force is generated between bearing pad and piston due to the normal piston force. Here, for half cycle the frictional force is opposes the torque

generated and further half cycle it supports torque. It happens because at the time of wobbling of pentagonal nut the direction of motion changes.The effect of frictional torque on total torque of motor has been evaluated as follows.
μ = Coefficient of friction = 0.2
R = Maximum radial distance of point at which friction force acting from the centre of shaft = 55 e-3 (m)
Friction force is, $F_r = \mu F_p$
Due to the frictional force wear of pentagonal nut occurs, to avoid this a ring shaped bearing pad of PEEK material is mounted on pentagonal nut which is easily replaceable after wear out and cost effective.

$$T_r = F_r[R - (E - E\cos(\theta))]$$

The variation in torque considering the friction in the motor is calculated and shown in Fig-4.

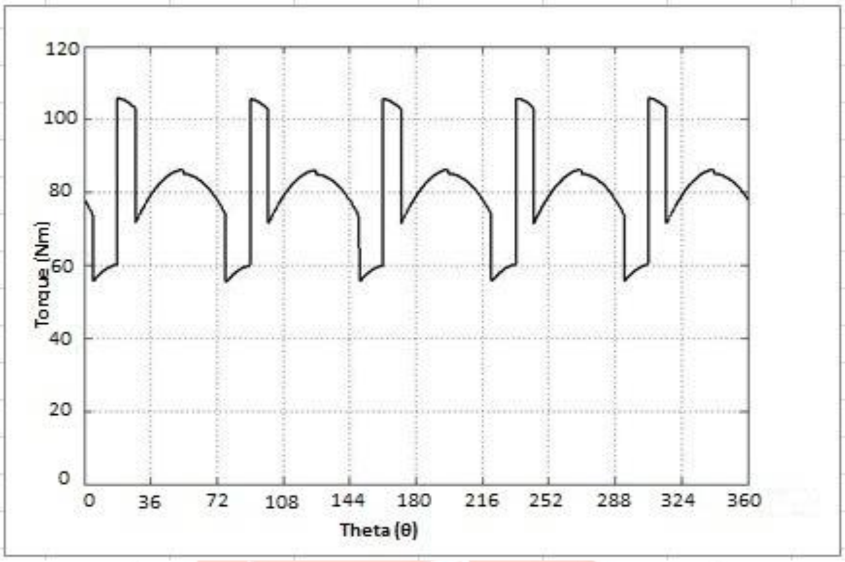

Figure 4: Total Torque by considering friction Vs Angle (θ)

Comparison of total torque generated by motor with negligible friction (theoretical torque) to the torque with friction (actual torque) is as shown in Fig.5. From the actual and theoretical torque mechanical efficiency calculated is 58.06% at 100 bar pressure.

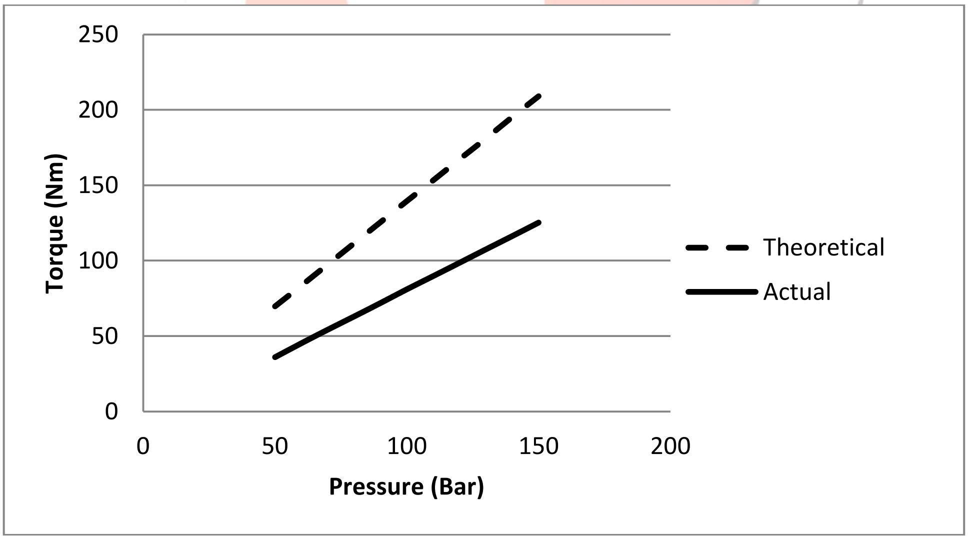

Figure 5: Torque Vs Pressure

iii. Torque Vs Speed Characteristics

The motor has two leakage path viz. axial and circumferential. These leakages have been estimated as follows:
The leakage flow rate between eccentric shaft and pentagonal nut axially is evaluated by equation of flow in concentric cylindrical annulus [4].
P_1 = Inlet pressure (N/m^2)
P_2 = Outlet pressure (N/m^2)
h = Radial clearance between shaft and pentagonal nut (m)
R_m = Mean radius of gap (m)
u = Dynamic viscosity of water (N-s/m^2)
L = Length of the flow path (m)

$$Q = \frac{\pi R_m h^3}{6uL}(P_1\text{-}P2)$$

To calculate the circumferential leakage, following equation of flow between parallel plates is used [5].
W = Width of the flow path (m)

$$Q = \frac{h^3 W}{12uL}(P_1\text{-}P_2)$$

From the total leakage, actual flow rate is calculated. Leakages contribute major part of total flow at low speeds. However at higher speed, contribution of these internal leakages is less significant. From theoretical and actual flow rate volumetric efficiency is estimated which is 93.97% at pressure of 100 bar and 60 rpm speed.
Hence, the Overall Efficiency of this *WH* Radial Piston Motor is 54.56% at 100 bar pressure and 60 rpm speed.
The variation of torque with speed has been evaluated and shown as speed-torque characteristics of the motor. At low speed and high pressure leakages reduces the available pressure at the piston and hence less torque is generated. However after particular speed torque remains constant as shown in Fig.6.
Speed Torque characteristics of motor:

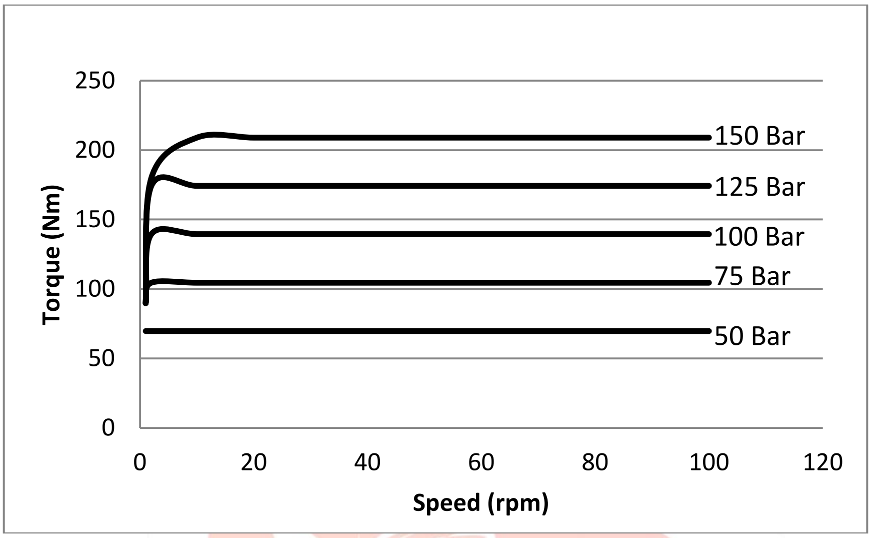

Figure 6: Torque Vs speed characteristics

V. Conclusion

Different type of motor studied and Inverted eccentric type design is more suitable for Water Hydraulic motor. Analysis for variation of Torque, various losses, various forces have been carried out. Mechanical, hydraulic and overall efficiency of the motor design has been evaluated at various operating pressures and Speed-Torque characteristics of the motor have been evaluated. It was found that overall efficiency of the motor is 54.56% at 100 bar pressure and 60 rpm speed.

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