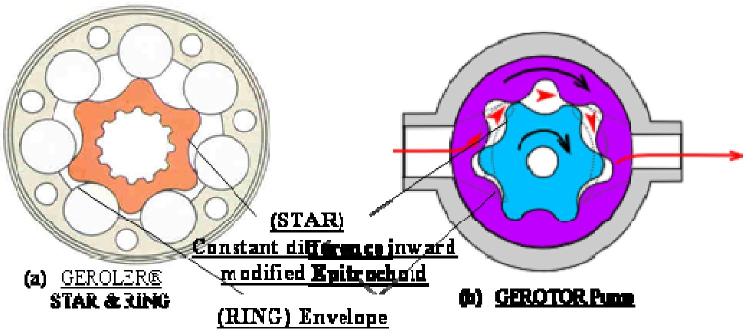
Chapter 1

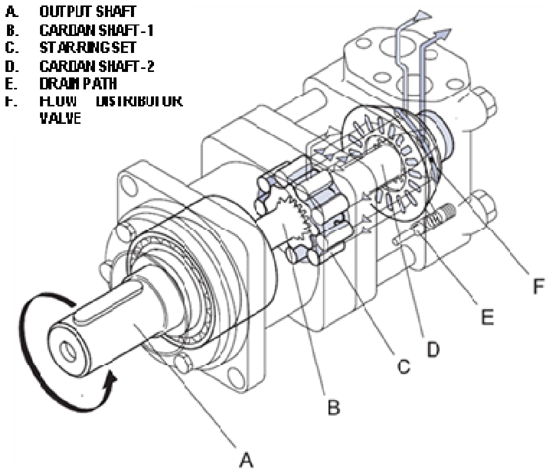
A Unique Hydrostatic motor with Epitrochoid Generated Rotor-Stator and its Performance Problems

1.1 Introduction

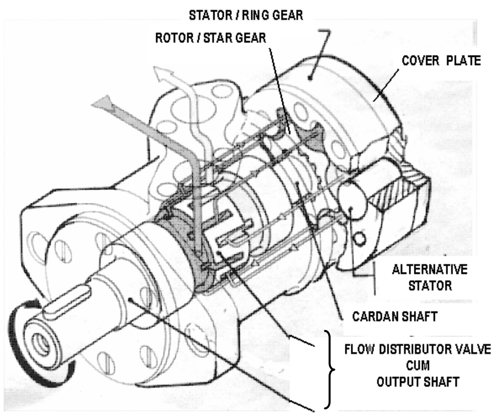
The rotary hydrostatic units, namely pumps and motor, having constant difference modified epitrochoids and envelopes [Ansdale, 1968, Coulbourne, 1974, Maiti, 1990[A], 1990[B]] as rotor and stator (or secondary rotor) possess many unique features comparing with other positive displacement hydrostatic units. Simplicity in construction, less movable parts, high output toque to weight ratio, low speed high torque output motor version, are few of them. However, uniqueness is mainly due to the geometric feature of the form closed rotor-stator, the gearing action in rotor-stator and the feature of flow distributor valve. Figure-1.1 shows a commercial unit, which is a variety of the described machines.

Such machines fall into the class of rotary piston machines (ROPIMAs) [Ansdale, 1968]. The term Rotary piston is associated with those volume displacement machines in which the trapped volumes in between a pair of mating parts, namely rotor and stator (or secondary rotor, i.e. non power transmitting but rotating member) undergo expansion-compression work during operation. In ideal condition i.e., without leakage the geometric volume displacement per revolution (swept volume) is independent of speed.





(c) ORBIT Motor with separated Flow Distributor (Disk) Valve



(d) ORBIT Motor with Flow Distributor (Pintle) Valve Integral with Output Shaft.

Fig.-1.1 : Epitrochoid generated Rotor-Stator and an Orbital Hydrostatic Unit.

In their simplest form, they rotate about their own geometric centers (i.e. central axis) fixed to a reference frame. However, movable axes system, similar to planetary gear trains, is also featured. It is to be noted that in rotating multi-piston hydrostatic units any piston-cylinder set can be made nonfunctional without affecting the basic kinematic feature of the machine. This, however, is not possible in case of the ‘rotary piston’ type hydrostatic unit. In the first case kinematic linkage controls the volume displacement, whereas change in inherent geometric configuration during rotation causes that in the latter case.

Another way of identifying the ROPIMAs and rotating piston machines is that in ROPIMAs the rate of change of volume (with motion) is directly proportional to the rate of change of the form closed areas of the chambers whereas it is due to the rate of change of stroke lengths of constant area pistons in latter case. Therefore, swash plate or multi-load cam and cam ring type positive displacement machines in which the cylinder block rotates, are grouped in the class of rotating piston machine whereas the considered hydrostatic units, which are gear type positive displacement units, are purely rotary piston machines.

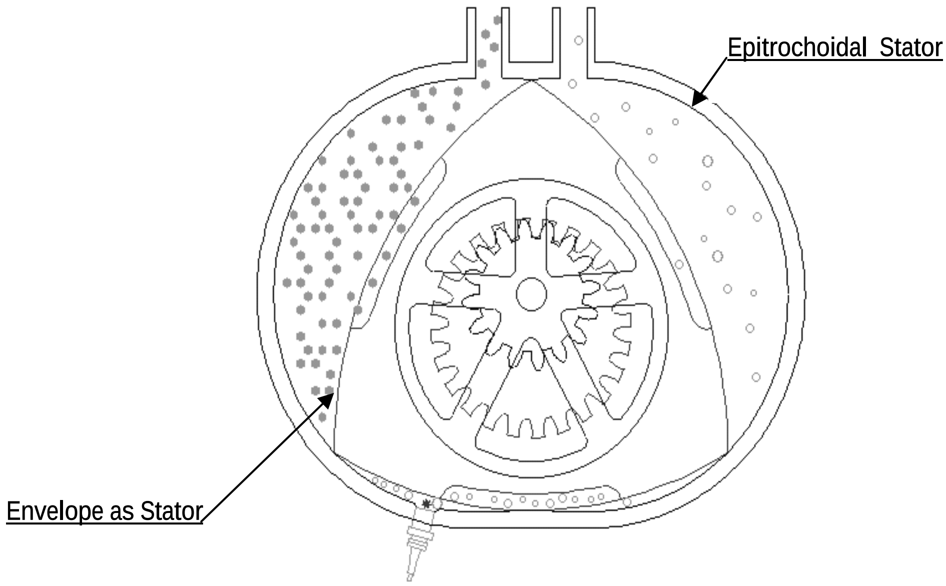


Fig.-1.2 : The Rotor-Stator of the Wankel Engine

The two elements that constitute chambers are generally known as ‘star’ and ‘ring’ (Figs.-1.1(a) and 1.1(b)). The constant difference modified epitrochoidal profiles are used to shape the outer profile of the solid star member (the inner member). The profile of the outer member, i.e., ring, is the envelope (i.e., conjugate) of the profile of the inner member. Alternatively, hypotrochoidal profiles can be used to shape the ring and their respective envelopes as star [Beard et al. 1991]. Epitrochoid can also be used to shape the inner profile of a hollowed body (which can be considered as ring), with its envelope shaping the star used in the Wankel engine (Fig.-1.2). However, the earlier one (i.e. epitrochoidal star and its envelope as ring) is more useful in designing hydrostatic units. Constant difference modification of the epitrochoid not only makes the active envelope as a circular arc but also increases contact load bearing capacity in gearing action in two elements.

The modified epitrochoid generator rotor-stator elements are also used for reduction gear units such as cycloid speed reducer [Pollitt, 1960, Botsiber et. al., 1956] (Fig.-1.3) and pin gearing set. However, the investigation report presented in this thesis was aimed at exploring some design issues relevant to the performance improvement of considered hydrostatic units. A brief description of the considered hydrostatic units in the next section is followed by a comprehensive literature survey which is done for identifying the issues that to be explored in the present investigation.

1.2 Hydrostatic units with Epitrochoid generated rotor-stator

In fluid power discipline hydraulic pumps and motors, which are essentially positive displacement machines, are generally called as hydrostatic units. The hydrostatic fluid power energy is the motive force. In power transmitting system circuit analyses hydrokinetic and hydrodynamic parts can be neglected with negligibly small compensation towards accuracy. Also, a type of pumps and motors possess almost similar identical features except some differences in flow distributor valve ports. Even, in some designs, a same unit can be used both as pumps and motors. Therefore, hydrostatic units is more generic name and used in this thesis.

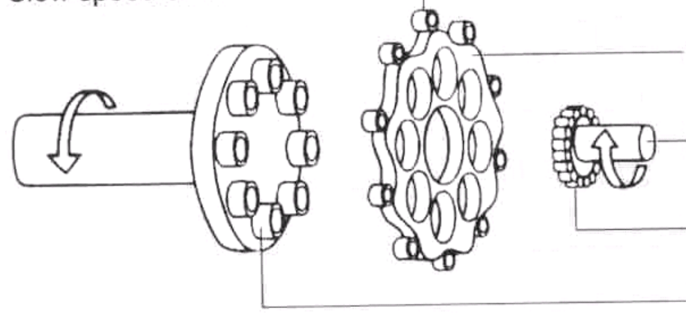


Fig.-1.3 : Cycloid Speed Reducer

Modified epitrochoid generated hydrostatic units commercially known as ORBIT ® motors, having epicyclic rotor and GEROTOR ® pumps and motors, having fixed axis rotors. The two elements, (with working profiles as modified epitrochoid and its envelope), that constitutes chambers are generally known as 'star' and 'ring' (Figs.-1.1(a) and 1.1(b)). The constant difference modified epitrochoidal profiles are used to shape the outer profile of the solid star member (the inner member). The profile of the outer member, i.e., ring, is the envelope (i.e., conjugate) of the profile of the inner member. It is to be noted that hypotrochoidal profiles could also be used to shape the ring and their respective envelopes as star [Beard et al. 1991]. Again, the unmodified (of a small amount modified to accommodate sealing elements) the epitrochoid can also be used to shape the inner profile of a hollowed body (which can be considered as ring), with its envelope shaping the star used in the Wankel engine (Fig.-1.2). However, considering limits in modification of epitrochoid, kinematics, load transmitting capacities at active contacts and few other characteristics, the earlier one (i.e. epitrochoidal star and its envelope as ring) is more useful in designing hydrostatic units [Maiti, 1990 (thesis)]. Constant difference modification of the epitrochoid not only makes the active envelope as a circular arc but also increases contact load bearing capacity in gearing action in two elements.

The number of lobes (Z-1) in the epitrochoidal profiled member and the number of lobes (Z) in the envelope profiled member is the ratio (of successive integers) of the two respective centrodes or describing circles.

Relative motions of the 'form closed' star and ring lobes in contacts, create expansion and compression of the chamber volumes constituted by the varying area between adjacent ‘active contacts’ (Figs.-1.1(a) and 1.1(b)) and the common width of the star-ring set. In said hydrostatic units, the sealing between chambers depends on these metal to metal active contacts which are ideally line contacts.

GEROTOR ® units are fixed axis units and both star and ring rotate in action. On the other hand, in an ORBIT ® unit, either the star or the ring remains fixed, and the other member rotates with an epicyclic motion (orbital or planetary motion). This results in higher number (the product of lobes in star and ring) of chamber actions in an input-output shaft (coupled to either member) as well as gearing action of transmission ratio equal to the lobe of the rotating member. This unit is advantageous for Low Speed High Torque (LSHT) applications and essential in hydrostatic motor. In most of the commercial applications the outer member remains fixed and the star and ring of ORBIT unit is usually called as ‘Rotor’ (the rotating one) and ‘Stator’ (the fixed one) respectively. Two motions of the rotor are observed in ORBIT Motors. These are:

(i) Revolving of the rotor about the central axis of the stator which happens to be usually the central axis of the machine unit, and

(ii) Rotation of the rotor about its own axis.

A closer analytical look reveals that the ratio of these two rotational (without considering the direction) equals to the number of lobes of the rotor. The output torque is transmitted from the revolving star through a cardan shaft, equivalent to a shaft with universal joints at two connecting ends. In a model the flow distributor valve is integral with the output shaft. In another model a separate disk valve is used (Fig.-1.1(d)) and it is driven by a separate cardan shaft.

To relate GEROTOR units with ORBIT units it can be explained as follows. Although the star-ring sets are same in both machines, from the kinematic point of view there are few distinct differences in these two machines. (However, it is to be noted that the name GEROTOR is also referred to as a generic name in some technical literatures [Henke, 1977]).

With the same star-ring set two different breeds of hydrostatic machines can be made, for the same power transmission (i.e. keeping the product of torque and speed same), by transmitting these two motions in different manners. These are High

Speed, Low Torque (HSLT), a unit for the first type (i.e. the orbital motion of the rotor about the central axis of the stator) and Low Speed High Torque (LSHT) unit for the second type (i.e. the motion of the rotor about its own axis) of machines. It can be shown that the underlying principle of the first type is equivalent to the fixed axis principle. However, these machines cannot be made of the variable displacement type without changing the speed or flow.

The first type can be used as positive displacement hydrostatic units, i.e. both pump and motor. However, the second type is concerned only to the hydrostatic motor unit. This is because of the reason that if an arrangement is used as a pump, a LSHT prime mover, which is redundant in respect to weight and size, will be required.

Research on kinematics, geometric design, stresses etc. of the rotor-stator set of hydrostatic units is still ongoing. The present investigation is aimed at exploring some design issues relevant to the performance improvement of considered hydrostatic units.

1.3 Literature survey

It is already mentioned in the preceding section that our concern is epicentered at some issues on the performance of ORBIT motor with epitrochoid generated rotor-stator set. The essential literature survey is done to arrive into the objectives of the present investigations. In this section a general discussion is made to brief the present state of art. More discussions relevant to the problem dealt are done referring to the earlier research work, in the concerned chapters and appendices. The LSHT Hydrostatic Transmission (HST) systems and problems at slow speeds and different LSHT motor constructions are also briefed in appendix.

1.3.1 Orbital construction, Rotor-Stator Profiles & Kinematics of ORBIT motors

The GEROTOR type ROPIMA was first proposed by Galloy in 1848 [White, 1988] as a rotary steam engine, although later it found its more appropriate application as lubrication pump. The orbital principle was patented in the midst of the

1960s, as reported in a technical bulletin of Danfoss, by Lynn I. Charlson – the founder of Char-Lynn Company, Minnesota, USA. The ingenuity in the invention was the arrangement of the distributing valve interacting with the expansion-compression phases which continuously change their positions with shaft rotation.

Franz Reuleaux (1829-1905) a German born ‘polytechnologist’ found through a cinematic exercise that if a two lobed closed epitrochoid is rotated through inverse cycloidal motion, an almost triangular shaped inner envelope is generated. He realized that these two profiles may constitute an engine working on an Otto - cycle along with a feature of constant ratio gearing. However the idea did not come into success until Felix Heinrich Wankel (1902–1988), another German technologist, could successfully develop a model of Rotary Combustion (RC) engine in 1957 which had a larger capacity of volumetric displacement as against a three cylinder reciprocating engine of the same overall size.

This success did not come overnight. Wankel [1968] had to work through the vast number of designs and inventions. A geometrical analysis of suitable profiles for ROPIMA was published in 1960 by Baier [1960]. Probably, the theorization of geometric design and kinematics of working principle could not take a rational shape until the B.S.A. Group research Centre of UK, could formulate the geometry of the profile and kinematics relations useful to the NSU/Wankel RC engine [1968]. Parallel outward shifting of the epitrochoid was also alluded in their work. It was required to accommodate the floating seals mounted in a groove made at the apex of the envelope (i.e. rotor).

Robinson [1981], who also worked on trochoidal expanders for the purpose of comparison of those with the vane type and reciprocating expanders, established the expressions for both the epitrochoid and its associated envelope modified to any constant difference i.e. parallel shifted. These expressions are also useful to design the rotor-stator profiles of GEROTOR and ORBIT units. Robinson and Lyon [1976] also presented some limitations on modifications. Almost in the same time a serious attempt was made by Colbourne [1974, 1975, 1976] to find out the geometric and kinematic relations required for the design of trochoidal rotary piston machines in a more generalized way. He used the approach of designing conjugate profiles.

It seems that a substantial amount of analytical work on trochoidal profiles useful to the ROPIMAs was also carried out in Japan; apart from many European countries, as Japanese automobile industry included Wankel engine in a few car models. However, all these analyses were concerned with the engine models similar to the NSU/Wankel engine and GEROTOR type volume displacement machines.

Nuhan and Oldzeski [1978] worked on Danfoss ORBITROL (i.e. Power Steering) unit in 1970s. They established some geometric relations, limits in modifications and the equations to calculate geometric displacement related to orbital principle.

A serious attempt was made by Maiti [1990] to establish a unified guideline correlating all the models in a coherent manner. Their interpretation can be realized from Table -1.1 [Maiti et al. 1990].

Researchers have followed the geometry of the fixed axis (GEROTOR) and floating axis (ORBIT motor) in different ways. While working on the fixed axes machines Stryczek [1990A, 1990B] has considered different cycloidal motions than Colbourne [1974, 1975, 1976] and Maiti [1990] have used. To generate a basic epitrochoid, Stryczek has considered the generating circle (centrode) rolls on the outer periphery of a fixed circle (centrode) which is the ‘describing’ or ‘base’ circle of the epitrochoid. This is contrary to that presented by Colbourne or by Maiti, where the inside of the rolling centrode rolls on outside of a smaller circle, the fixed cenrode, while generating an epitrochoid. The sizes of these centrodes (circles) are different and even the base circles are not same for the same epitrochoid. Naturally all the representative parameters are not same. In both cases the working profile is generated then by shifting the unmodified profile parallely at a constant distance. However, such a double generation method had already been established by Veldkamp [1979], a Dutch mathematician, following the theory of De La Hire, a French mathematician. According to Veldcamp- ”A cycloid, which is neither a circle nor a straight line, can be produced by at most two cycloidal motions”. Following these theories Maiti [1990] have shown how useful epitrochoidal profiles for

GEROTOR and ORBIT units can be generated by above mentioned both type cycloidal motions.

Beard et al. [1991, 1992], Shung and Pennock [1994], Monaco et al. [2000] and Demengo et al. [2002] have directly generated the modified epitrochoidal profile using the pin type ring gear as a generating tool. The mathematical formulation, by co-ordinate transformation using homogeneous matrix, is presented in more generalized and useful form by a group of researchers being associated with Litvin [1996, 2001, 2004].

Later researchers have used one of these methods in designing useful epitrochoid for hydrostatic units, cycloid speed reducer and similar gear units. They found one is easier than other two to follow. However, all these evoked an idea of examining whether these three methods can be unified, which has been attempted in this dissertation.

Gamez-Montero [2006] has considered frictions at contacts in their FEM analyses of trochoidal gear pump. Then Gamez-Montero and Codina [2007[A]] has evaluated the flow characteristic of a trochoidal-gear pump analytically and experimentally to understand the performance of a trochoidal-gear pump. Again Gamez-Montero and Codina [2007[B]] estimated the leakage, instantaneous flow, the flow ripple experimentally and then validated the bond graph model with the experimental results. Then Gamez-Montero et al. [2009] presented a new tool that is going to lead the designer to a better design by improving performance indexes of a newer GEROTOR pump and also to reduce manufacturing costs by reducing time in the design stage. It is worth mentioning that Gamez-Montero along with his associated researchers, have also worked on involute type gear pumps, both theoretically and experimentally, targeting their performance improvement [Castilla et al., 2009 & 2010] and investigated similar phenomenon in these machines as in GEROTOR units.

Most recently the pattern of leakage flow through the active contacts is studied by Maiti et al. [2015] using CFD analyses in support of the experimental results by Stryczek et al. [2014].

Table- 1.1. Kinematic relations among possible machines with epitrochoid generated rotor and stator [Maiti, 1992].

Description			Angular speed				Speed ratio	Phase angle γ_o^o		Application
Type		Input/Output	WRT	Fixed	Frame	Trochoid WRT Envelope ω	$i_t = \omega/\omega_r$	Single cycle	Combined	
Machine	Motion	Shaft coupled to	Trochoid	Envelope	ARM			$\pi Z/\Lambda$	π/Λ	
1	Fixed	Trochoid[b]	$\omega_r = \omega_{ef}$	$\omega_{cf} = \frac{Z-1}{Z}\omega_{ef}$	0	$\frac{1}{Z}\omega_{ef}$	$\frac{1}{Z}$	$\frac{\pi Z}{Z-1}$	$\frac{\pi}{Z-1}$	Pump, motor, compressor, engine etc. with fixed volume
2	Axis	Envelope	$\omega_{ef} = \frac{Z}{Z-1}\omega_{cf}$	$\omega_r = \omega_{cf}$	0	$\frac{1}{Z-1}\omega_{cf}$	$\frac{1}{Z-1}$	π	$\frac{\pi}{Z}$	
3	Epicyclic	Trochoid	$\omega_r = \omega_{eo}$	$\omega_{co} = 0$	$-(Z-1)\omega_{eo}$	ω_{co}	1	$\frac{\pi}{Z-1}$	$\frac{\pi}{Z(Z-1)}$	Motor with rotary valve
4	Epicyclic	Envelope	0	$\omega_r = \omega_{co}$	$Z\omega_{co}$	$-\omega_{co}$	-1	$\frac{\pi}{Z-1}$	$\frac{\pi}{Z(Z-1)}$	
5	Epicyclic	ARM[a] (Trochoid fixed)	0	$\frac{\omega_{co}}{Z}$	$\omega_r = \omega_{co}$	$\frac{-\omega_{co}}{Z}$	$-\frac{1}{Z}$	$\frac{\pi Z}{Z-1}$	$\frac{\pi}{Z-1}$	Pump, motor, engine etc. with rotary valve
6	Epicyclic	ARM (Envelope fixed)	$\frac{-\omega_{co}}{Z-1}$	0	$\omega_r = \omega_{co}$	$\frac{-\omega_{co}}{Z-1}$	$-\frac{1}{Z-1}$	π	$\frac{\pi}{Z}$	

a Planet carrier, b Modified or unmodified epitrochoid.

c input/output angular displacement between two dead centre; indices e, c, a indicating the rotational frequency of the trochoid envelope and arm, respectively; indices f, o indicating fixed axis and epicyclic model respectively.

1.3.2 Major Problems in ‘ORBIT’ Motors

The orbital rotor hydrostatic motors are also no exception of the general low speed problems stated in appendix-1A. The general problems are as follows.

The rotor in such a machine virtually is of ‘floating axis’ type. As observed by the author the rotor-stator set is subjected to three distinguishable major actions simultaneously. These are:

i) expansion – compression, (i.e. suction-discharge) ,
ii) high ratio gearing and
iii) high load bearing.

Such unique features of the machine give a separate identity of the unit within the LSHT class. On the other hand they complicate the design and analysis. The detected problem areas, which are to be analyzed to predict the performance of such a ROPIMA type hydrostatic unit, are categorized as follows.

(i) Active Contact Regions:

The form-closed contact zone can be designated as ‘Active Contact Zone’ (ACZ). Such as metal to metal higher pair contact has to separate, at a particular phase during rotation, the high pressure chamber from the low pressure chamber. (This phase of contact is designated as ‘Transition contact’ (TRC) or (TR)). Nevertheless, the active portion of the integral envelope is replaced by the cylindrical roller, placed in partial bush, in some models (Fig.- 1.2). It is quoted in the manufacture’s catalogue that the "friction occurs exclusively in the bearing of the rollers and the hydrodynamic lubrication between the rollers and gear rim reduces it to a minimum, independent of the operating pressure".

Obviously, the behaviors of these contact zones have a major role in the performance. Apparently, the following active contact problems are to be analyzed:

a) Contact stresses and deflections or gaps generated at the contacts,

b) Rolling -sliding behavior with integral and roller type envelope,

c) Tribological and sealing behaviors and

d) Losses through the active contacts.

ii) Star motion on valve plate and side plate, and leakage through the capillary passage in between.

The capillary passage between the walls of the inner and outer member (one of them is valve plate) or of a stationary casing (Fig.-1.1) can be designated as 'Slip Flow Region' (SFR). The gaps between them should be minimized to reduce leakages. On the other hand, it is desired to have there a lubrication film always acted to minimize the friction. The following behaviors which will affect the performance need to be studied:

a) Sliding of the surfaces under epicyclical notion,

b) Pressure distribution at boundaries and capillary passages,

c) Tribological behavior and

d) Losses through the region.

iii) Flow Distributor Valve:

A simple kidney port valve can be used for axis ROPIMA (gerotor) hydrostatic units (Fig.-1.1(b)) many research reports are available for the analyses such values. The multi-port spool (or pintle) type distributor valve which is used in the orbital unit has a different configuration. This valve rotates at the same speed of the output shaft. The spool valve unit, through which the common DC flow gets distributed to the different chambers through separate channels on it, is also used as a journal of the output shaft in some model.

The durations of opening and closing of the ports for flow in and flow out phases as well as at dead zones, are important to bring a balance between the leakage through the port and the squeeze or expansion of the trapped volume at the dead zones. By no means, the valve interactions can be neglected in the performance analyses. In case of higher capacity ORBIT motor, separate bearings are used for transmission shaft [Danfoss]. Hydrostatically balanced valve, used in those designs, is known as commutator valve which again needs separate analysis. In brief, valve performance consists of the following characteristics:

a) Interaction of the port with the valve (i.e. transients),
b) Leakage and viscous_ drag losses through the valve and
c) Tribological behavior.

iv) Transmission shaft:

The Cardan shaft, used to transmit the motion and torque from the orbital rotor to the central shaft, consists of a rounded tooth gear coupling at both the ends. Although the number of teeth is large yet it has its own dynamics. It is also a source of 'windup' problem. Therefore, it has the role on motor performance.

1.4 Objectives and Scope

Analyses on the problems at active contacts, one of the identified problem prone areas, are the subject of the present investigation. In case of ORBIT motor, with floating axis rotor, all forces are transmitted through the active contacts and in case of fixed shafts (Gerotor unit), bearings also take load for equilibrium. In any case in finding the loads at active contacts the problem is statically indeterminate. Nevertheless, in some active contacts a gap is generated even when the contact is separating a high pressure chamber from the adjacent low pressure chamber. This causes inter-chamber leakage through an orifice of rectangular area- the product of the generated gap and the width of the active contact (i.e., the width of the rotor-stator). Some manufacturers provide oversize profiles (Interference fit) in such form closed contact machines to reduce leakage losses.

Maiti and Nagano [1999] proposed a method of estimating starting torque of ORBIT (also called load holding torque) motors with respect to the fittings of star and ring of a few different sizes. They used trial and error method [Maiti, 1993] estimating deformations at active contacts and loads. They observed an unbalanced torque (due to residual and unbalanced forces at active contacts) when none of the chambers are in neutral phase.

It is apparent that behaviours at active contacts have a great role in the performance of such hydrostatic units. Investigations on some behavioural characteristics at active contacts in ORBIT motors are aimed at, which are detailed next.

The main objectives of the present investigation are to analyze the active contact zones, development of deformation or gaps at those contacts and their effects on the performance of ORBIT motors. At the earlier stage of the present investigation it was realized that various geometric methods used to shape the star to be unified so that our analyses could be used by all interested researchers. Therefore, the present investigation envisaged at:

- Unification of various geometric design methods, proposed by different group of researchers, to shape the cycloidal class (modified epitrochoidal) of profiles used to shape the star element of hydrostatic units.
- Determining effects of fit (in terms of interference) of star and ring on deformation and gap formation at active contacts using a trial and error method, proposed earlier [Maiti 1993], in estimating load shared by multiple active contacts.
- Development of a closed form solution in lieu of above mentioned trial and error method.
- Estimation of load holding torque and unbalanced torque, and effect of fit (of star and ring) on them.
- Estimation of gaps, if generated, at active contacts separating high pressure chamber from adjacent low pressure chamber, which causes inter-chamber leakages.

1.5 Organization of the Thesis

Following this introductory Chapter-1, which includes literature survey and objectives, the unification of profile geometric design methods, is presented in chapter-2. The analysis of active contacts consisting of effects of fit (in terms of interference) of rotor and stator on deformation using an earlier proposed trial and error method and an analytical method, outcome of the present investigation, is presented in chapter-3. Computations for deformations and gaps, estimation of load holding torque and unbalanced torque and effect of fit on them and flow pattern analysis (through gap) are presented in chapter- 4. In epilogue, the chapter- 5, outlining the summary of the present investigation concluding remarks and future scope of work, are presented. Useful derivations and information are presented in section-Appendices which are placed after References.