Inter Chamber Leakages in Orbit Motors—Estimation by Modeling and Simulation in FEM and Fluent® Environment

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Inter Chamber Leakages in Orbit Motors- Estimation by Modeling and Simulation in FEM and Fluent® Environment

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Abstract. An analysis is carried out to predict inter-chamber leakage flows through the two transition active contacts, which separate the high pressure chambers from the adjacent low pressure chambers, in the cycloidal class toothed star-ring of ORBIT® motors. Among geometrically form closed contacts which separates chambers from each other, few active contacts support high reaction loads during the process of transmitting torque in such unique LSHT hydrostatic units. Contact deformations in those contacts generate gaps in the other contacts for a partial period of time. High inter-chamber leakages occur through such gaps at transition active contacts. In an attempt to visualize the characteristics of such leakages, which contribute towards the poorer leakage characteristics of such machines, detail mapping i.e., magnitudes, rotational position etc., of such gaps of a commercially available unit, are carried out. For estimating gaps FEM technique is used. The FEM results have very good agreement with the results predicted earlier using trial method. Such gaps are difficult to measure as the contact positions are inaccessible to equip any conventional measuring instrument. The characteristics of leakage flows through such gaps are then established by CFD analysis using Fluent® in Ansys environment.

1. Introduction
The GEROTOR type ROPIMA (Rotary Piston Machines) having geometrically form closed chambers, was first proposed by Galloy in 1848 [1] as a rotary steam engine, although, later the same design principle has been adopted to develop a unique class of positive displacement machines like rotary piston combustion (Wankel) engines, lubrication pumps, hydrostatic units (pumps/motors) and compressors. Such ROPIMAs come under the category of positive displacement machines, with fixed axis rotating star and ring [Figure 1(a)] of cycloidal class profiles. Their operations/working principles are more similar to the common and conventional involute toothed internal gear pumps and motors. GEROTOR pumps and motors, the fixed axis units where both star and ring rotates [Figure 1(a)], possess High Speed Low Torque (HSLT) features. It is to be noted that the ring may be with integral lobes or separate rollers as shown in Figures 1(a) and 1(b) respectively. The models shown in Figure 1 are of constant difference modified epitrochoidal star and its envelope as ring. The active portions of the envelope are circular arcs. The orbital rotor (with the same elements) 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. In such a unit, usually the star in epicyclic motion experiences rotary motion about its own axis (connected to the torque shaft) and revolving motion about the fixed ring axis. Due to kinematic advantages such a unit is used as motor only. Such a unit, popularly known as ORBIT ® motor, possesses Low Speed High Torque (LSHT) feature.
(a) Epitrochoidal Star and Ring with Integral Lobes.  
(b) Epitrochoidal Star and Ring with Roller Lobes.  

Figure 1. Typical epitrochoidal Star and Ring.

Gamez-Montero and Codina [2] has evaluated the flow characteristic of a trochoidal (modified cycloidal) -gear pump analytically and experimentally to understand the performance of this type gear pump. Coulbourne [3] has shown a method of estimating contact deformations in such machines. Maiti [4-6] has done exhaustive investigations on estimating such gaps. To solve the statically indeterminate problem, as there are multiple contacts, a trial method is proposed. Later an analytical method [7, 8] is also proposed. Gamez-Montero et al. [9] have established a method of estimating contact deformations in trochoidal gear (GEROTOR) pump using FEM. Bonandrini et al. [10] presented a complete and original method to analyze both the epitrochoidal and the hypotrochoidal ROPIMA type HST units. In the present investigation, the gaps at transition contacts are estimated at first for different angular position of torque transmitting shaft. Then the CFD analyses are done to estimate leakage considering the leakage path geometry and pressure profile.

2. Estimation of deformation / gap at active contacts due to fluid pressure

The calculation of deformations and generated gaps at the active contacts with respect to the relative angular positions of star and ring is the main task prior to the leakage analysis. In the present investigation both analyses are done using numerical techniques in Ansys environment. It is assumed that the star and ring are perfectly form closed and there is no manufacturing error. Analyses are carried out with respect to the ORBIT unit, in which form closed star is considered as the floating axis member. The gear coupling in the star transmits torque to the output shaft through cardan shaft. All radial loads supported by the active contacts and not transmitted to the output shaft. Few chambers are in high pressure one side (chambers between contact points 1 to 4 as an instant as shown in Figure 1(b) & Figure 2 of the imaginary plane and in low pressure in other side. It may be considered that the fluid pressure acts as the uniformly distributed load [6] on the plane joining the higher pair contacts at lobe 4 and lobe 1 The net forces [Figure 2] due to deformations at some active contacts, must be balanced with the pressure force. As well as, all moments are also to be balanced. These can be expressed as [4,6]:

\[ \mathbf{F}_i = \sum_{n=1}^{z} \mathbf{F}_n \]  

\[ |\mathbf{F}_i| = \Delta p L_b \]  

(1)  

(2)
\[ M_i = \sum_{n=1}^{Z} (r_{in} \times F_{i_n}) = r_i \times F_i \]  

Based on Hertzian contact theory and on simplification the contact deformation can be expressed as:

\[ \delta_n = \frac{8F_n}{\pi b} \left[ \frac{1 - \nu^2}{E} \left( 1 + \frac{\pi}{4} \right) \right] \]  

3. Trial and error method

Deformations \( (\delta_n) \) are estimated by iterating the infinitesimal displacement of star centre assuming the star is rigid except allowing local contact deformations, and solving equations 1 to 4 till the equilibrium is achieved. Resolving the displacement vectors in normal direction of the lobes and the values of deflection/gap at all contact points are calculated. The values for transition active contact points (in this case 1 & 4) are recorded for further analysis. After the shaft rotation of a cycle i.e. \( \xi_o = \pi / (Z-1) \) degree in case of an ORBIT unit and \( \pi / (Z-1) \) degree in case of a GEROTOR unit (torque transmitting shaft is connected to star unit) the phase changes [4]. For next \( \xi_o \) contacts 1 & 5 will be in transition (clockwise rotation for torque shaft).

![Figure 2. Deformations and Hertzian contact forces at active contacts due to fluid pressure](see also Figure 1(b)).

4. FEM modeling and analysis in ANSYS

The main focus for the geometric modeling of ORBIT motor is on the theoretical profiles of two major components: star and ring. Basically, three types of software have been used these are Matlab, Solid Works and Ansys. SOLID186 element has been chosen for analysis. In this model min. mesh size is 0.00021994 mm. and max. mesh size is 1.09970 mm. So, the number of nodes and elements are 717490 and 166137 respectively. Regarding boundary conditions consider stator part of the orbit motor is rigid and star-roller contacts, stator-roller contacts are frictional (C.O.F- 0.15). The formulation used here is augmented Lagrange and operating pressure is 5 MPa. The deformation analysis is carried out on FEM model varying the shaft rotational angle \( \xi \) from 0° to 8.57° \([2\xi_o=2\pi/Z(Z-1)]\) degree (one cycle/phase) in twelve steps.
5. Result and discussion based on FEM model
As revealed from graphs in Figure 3 (a & b), a gap is generated at transition contact point 4 [Figure 1(b) and Figure 2 point A] from the beginning of the cycle/phase i.e., $\xi=0^\circ$. The contact 4 is separating the chamber C3 and C4, where C4 just started expanding i.e., in HPZ. The chamber C3 is continuing compression phase, i.e., it is in LPZ. Gaps start at the beginning of $\xi=0^\circ$ and resulting inter-chamber leakage from C4 to C3. In the present case it continues up to $\xi=4.285^\circ$. In Figure 3 (a & b), which are very prominently shown the gap or deformation found in trial and error method have good agreement with the deformation and gaps comes from FEM analysis (using Ansys software).

![Deformation and gap at active contacts in lobe 1, 4, and 5.](image)

**Figure 3(a).** Deformation and gap at active contacts in lobe 1, 4, and 5.

![Deformation and gap at active contacts in lobe 2, 3, 6 and 7.](image)

**Figure 3(b).** Deformation and gap at active contacts in lobe 2, 3, 6 and 7.

6. Analysis of leakage model in Ansys® Fluent
After mapping the gaps through the transition contacts for this model, leakage through the gaps require to be estimated. Patterns of leakage flow will be studied through CFD modeling in Fluent® environment. Basically, three types of software have been used for three main stages of the simulation. These are Matlab, Ansys apdl for modelling and Fluent module in Ansys work bench. 2-D geometric 1st lobe, 4th lobe and 5th lobe contact models are imported in fluent module for meshing. For 1st lobe min. and max. mesh sizes are 0.002226 mm. and 0.42 mm, corresponding nodes and elements are 2190 and 1850 numbers. Similarly for 4th lobe min. and max. mesh sizes are 0.000381834 mm. and 0.3 mm, corresponding nodes and elements are 4796 and 4320 and for 5th lobe min. and max. mesh sizes are 0.00037304 mm. and 0.2 mm , corresponding nodes and elements are 5270 and 5030.
ξ  
Gap at 1st. lobe  
lobe  
( nδ , mm) 
Velocity  
( nv , m/s) 
at 1st. lobe 
Flow Rate 
(10-8) 1st. lobe 
( l,nq , ... gaps at 5 MPa. 
Figure 5. Leakage oil velocity through gap at transition contact at lobe 5 ( ξ = 4.286°) at p=5 MPa.

| ξ   | Gap at 1st lobe ( δ1 , mm) | Velocity ( v1 , m/s) at 1st lobe | Flow Rate (10^-8) 1st lobe ( q1 , m^3/sec) | Gap at 4th lobe ( δ4 , mm) | Gap at 5th lobe ( δ5 , mm) | Width ( b , mm) | Velocity ( v5 , m/s) | Flow Rate (10^-8) at 4th and 5th lobe ( q5 , m^3/sec) |
|-----|-----------------------------|---------------------------------|----------------------------------------|-----------------------------|-----------------------------|----------------|---------------------|----------------------------------|
| 0°  | 0.00160055                  | 14                              | 0.97                                   | 2.17354                     |
| 1°  | 0.00198987                  | 14                              | 1.14                                   | 3.175829                    |
| 2°  | 0.00493141                  | 14                              | 1.54                                   | 10.63212                    |
| 3°  | 0.00588309                  | 14                              | 1.65                                   | 13.58993                    |
| 4°  | 0.00908418                  | 14                              | 2.12                                   | 26.96185                    |
| 4.285° | 0.01090102                | 14                              | 2.34                                   | 35.71173                    |
| 4.286° | 0.0164380                  | 14                              | 2.55                                   | 58.6838                     |
| 5°  | 0.0190335                   | 14                              | 2.64                                   | 70.34789                    |
| 6°  | 0.0015572                   | 0.96                            | 2.0929951                              | 0.0210234                   |
| 7°  | 0.0060561                   | 2.23                            | 18.9072066                             | 0.0193796                   |
| 8°  | 0.0109010                   | 7.72                            | 117.818180                             | 0.0151403                   |
| 8.57° | 0.0121122                  | 15.5                            | 262.835608                             | 0.0157459                   |
Figure 4 shows 2-D meshed model for shaft rotation of $\xi=4.285^0, 4.286^0$ and $8.57^0$. Regarding the boundary condition, consider the star wall and ring wall are stationary.

7. Result and discussion based on Fluent® model
After the simulation, the velocity profile for $\xi=4.285^0, 4.286^0$ and $8.57^0$ are shown in Figure 5. The Fluent analysis is defined with 2-D, pressure based Navier Stokes, and laminar flow. The instantaneous leakage flow rate through the gap at contact in $n^{th}$ lobe can be estimated as:

$$q_{ln} = v_n (\delta_n \times b)$$

(5)

Based on Equation-5, the leakage flow rate at 5 MPa were calculated and shown in table-1.

8. Conclusion
A method of estimating flow through the narrow gap, generated at transition contacts separating a high pressure chamber from the adjacent low pressure chamber in ORBIT motor, is established through an analysis using Fluent. The generation of gap at transition contacts occurs at certain phases, due to deformations at form closed contacts, while transmitting torque. Such gaps are estimated using FEM in Ansys in the present investigation. Results have good agreement with a trail method developed earlier. The estimated quantity of such leakage flow indicates the relatively poor volumetric efficiencies that are shown in product catalogues.

9. Abbreviations

| CFD   | Computational Fluid Dynamics.          |
|-------|---------------------------------------|
| FEM   | Finite Element Method.                |
| HPZ   | High Pressure Zone.                   |
| LPZ   | Low Pressure Zone.                    |
| ROPIMA| Rotary Piston Machine.                |
| TEM   | Trial and Error Method.               |

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