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Research on No-Contact Hydraulic Dynamic Seal Characteristic based on CFD

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Abstract

Non-contact hydraulic seal (clearance seal) decrease the leakage by the small clearance between the seal. Non-contact seal is the seal form is very simple. The sealing effect depends on the size of the clearance and pressure difference, the length and parts of the sealing surface quality. Among them, the clearance size of the greatest impact on the sealing performance. The hydraulic systems sealing mathematical and computational fluid dynamics(CFD) model are presented to estimate the impact of eccentricity ratio, seal clearance and pressure are has to hydraulic force and leakage. These factors should be considered in the practical engineering.

Keywords: *Hydraulic Pressure; No-contact Seal; Leakage; CFD*

1. Introduction

Hydraulic systems sealing is an important guarantee to work, it will increase the hydraulic components of the system leakage if sealed properly. Increase system energy losses, lower efficiency of the system and environmental pollution will result in serious system can't normal work. Sealed and seal design choices directly affect the number of hydraulic system performance, so seals and seal reliability and service life is a measure of the hydraulic system and component design, manufacturing and important indicator of quality [1-2]. For the hydraulic systems, the understanding and knowledge of seal mechanism and seal form are beneficial for the maintenance and repair of hydraulic systems, which can improve the efficient use of machinery.

As the clearance between in hydraulic sealing systems, friction is small, less heat and can be used more long time. Hydraulic sealing is different the other sealing material, it has simple and compact structure. Non-contact seals are generally used for dynamic sealing, such as pumps and motors between the plunger and the plunger hole sealed. The disadvantage of non-contact seal is due to the presence of a clearance, and therefore can not completely prevent the leakage, so it is very important to know the influence law of the leakage and hydraulic force.

2. Nonlinear Hydraulic Dynamics Seal Model

Several assumptions were made in this research. The first assumption is the rotor is whirling in the forward direction. The next is that the fluid behaves as an ideal fluid. The ideal fluid assumption is at high temperatures and low pressures, but in this research it was

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used because the non-ideal fluid assumption would be too difficult to implement in CFX. Another assumption is that there was a no-slip condition inside of the seal. The no-slip condition is a good assumption, because without it, seals wouldn't function in the way they were designed to. A final assumption is the walls within in the model are smooth. Wall roughness will have an effect on the flow through the labyrinth seal, but the smooth wall assumption was made because any wall roughness setting would have been an arbitrary guess. Hydraulic systems rotor-sealing model [3-5] shows in Figure 1. It can be known that the hydraulic systems sealing model consists of disk, rigid shaft, journal bearing, sealing and hydraulic oil.

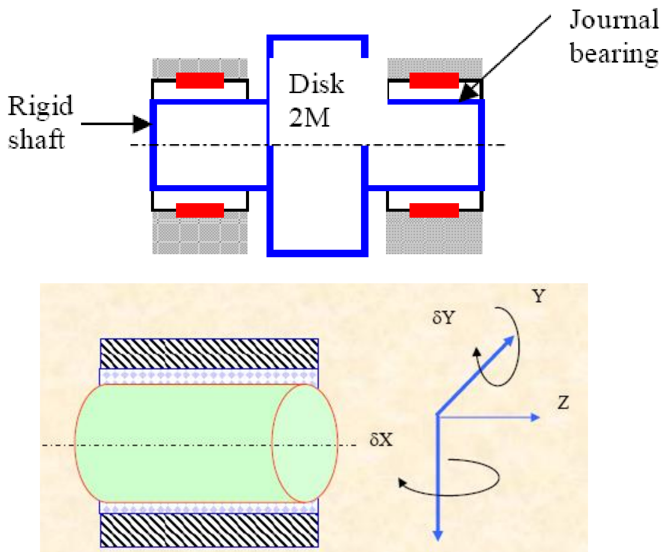


Figure 1. Hydraulic Systems Rotor-sealing Model

Continuity equation of nonlinear hydraulic control volume I:

$$L_i \frac{\partial(\rho_i H)}{\partial t} + L_i \frac{\partial(\rho_i H U_{1i})}{R_{s1}\partial\theta} + \dot{m}_{i+1} - \dot{m}_i + \dot{m}_{ri} = 0 \qquad (1)$$

Continuity equation of nonlinear hydraulic control volume II:

$$L_i B\left[\frac{\partial\rho_i}{\partial t} + \frac{\partial(\rho_i U_{2i})}{R_{s2}\partial\theta}\right] - \dot{m}_{ri} = 0 \qquad (2)$$

Circumferential direction momentum equation of hydraulic control volume I:

$$L\frac{\partial(\rho_i H U_{1i})}{\partial t} + \frac{L}{R_{s1}}\frac{\partial(\rho_i H U_{1i}^2)}{\partial\theta} + \dot{m}_{ri}U_{0i} + \dot{m}_{i+1}U_{1i} - \dot{m}_i U_{1i-1} = -\frac{L_i H}{R_{s1}}\frac{\partial P_i}{\partial\theta} + L_i(\tau_{j\theta i} - as\tau_{s\theta i}) \qquad (3)$$

Circumferential direction momentum equation of hydraulic control volume II:

$$L_i B \frac{\partial(\rho_i H U_{2i})}{\partial t} + \frac{L_i B}{R_{s2}} \frac{\partial(\rho_i H U_{2i}^2)}{\partial \theta} - \dot{m}_{ri} U_{0i} = -\frac{L_i B}{R_{s2}} \frac{\partial P_i}{\partial \theta} + L_i (\tau_{j\theta i} - a r_i \tau_{s\theta i}) \quad (4)$$

Scharrer used the leakage equation:

$$m_i = \mu_0 \mu_i H \sqrt{\frac{\sqrt{(P_{i-1}^2 - P_i^2)}}{RT}} = P_i H_i W_{1i} \quad (5)$$

μ_0 is defined by Vermes (1961) by:

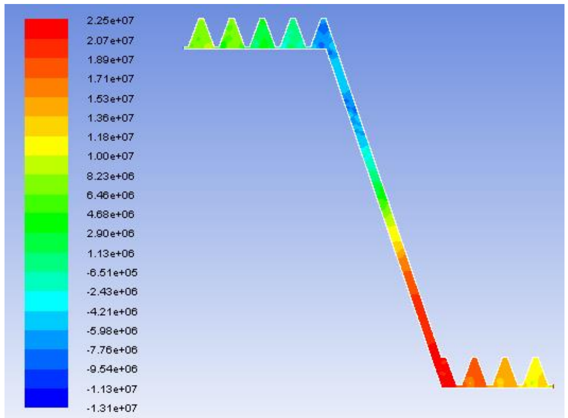
$$\mu_0 = (1 - \alpha_i)^{-1/2} \quad (6)$$

Where,

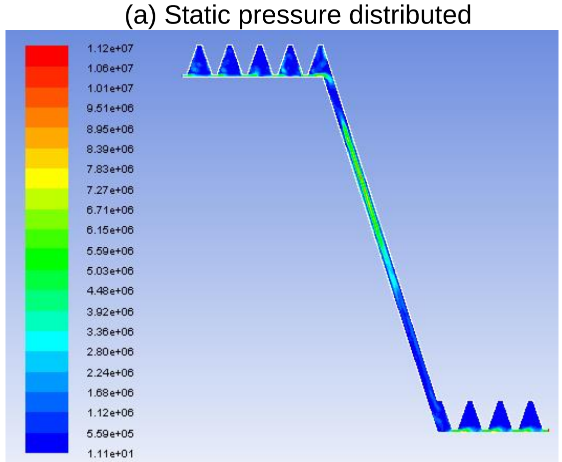
$$\alpha = \frac{8.52H}{(L_i - T_{wi}) - 7.23H} \quad (7)$$

3. Hydraulic Pressure Effect Study

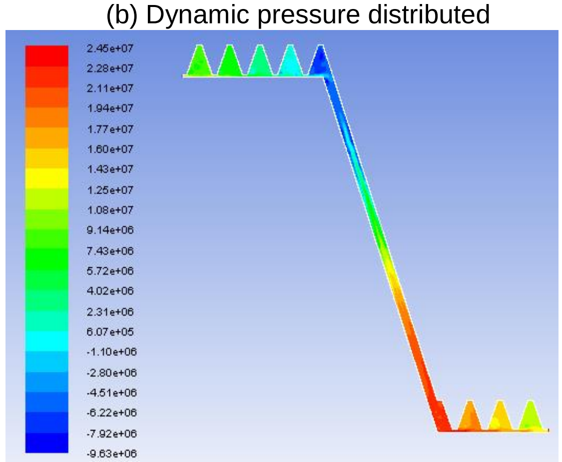
The mesh was created in ANSYS Workbench using the CFX-Mesh option. This option focuses on creating a mesh that has the necessary characteristics for use in a CFD solver. A CFD mesh differs from other solid meshes because it focuses on refining the flow in boundary layer regions and has different element aspect ratio criteria. There are several drawbacks to the CFX-Mesh program. The first is while it is easy to specify the desired overall mesh characteristics, it can be difficult to refine the mesh in the exact way that the user wants without a significant amount of time spent varying the mesh controls and options. Another drawback is the program only “free-meshes” with tetrahedrons. Overall, it seems that it would have been easier to make a structured mesh to satisfy the desired mesh characteristics in this research. Additionally, it is objectionable that CFX-Mesh only generally states that the created mesh has elements with undesirable aspect ratios. This requires the user to post process the mesh and manually hunt for those elements. Figure 2 shows hydraulic pressure distribution through seal, it includes static pressure distribution, dynamic pressure distribution and total pressure distribution [6]. In Figure 2, there are red, yellow, green and blue 4 basic colors from inlet to outlet, and the pressure is improve from the blue to red. It can be seen that the pressure drop is constant from pressure inlet left to pressure outlet right, and the pressure is almost equal in the same tooth cavity interior. From the dynamic pressure distribution, we can see that pressure drop mainly occurs at the tooth clearance [7]. Figure 2(a) is static pressure distribution in the streamwise stations of seal, the axial static pressure is lower trapezoidal distribution. There is no pressure change in the tooth cavity, but it has a great pressure drop when the stream flow the tooth clearance, it is because part of the flow is changed into flow speed from static pressure.



(a) Static pressure distributed



(b) Dynamic pressure distributed



(c) Total Pressure Distributed

Figure 2. Hydraulic Pressure Distributed

The whirl speed study had lower solution times in general because it was converged to the residual level, while the eccentric study was converged. There is a discrepancy because after the whirl speed study, it was determined that the residual level was preferable, so the next study performed (the eccentric study) used the new residual value. In general, reducing the converged residual level increases the solution time because it takes more iterations to reach a smaller residual. On average, 4 meshes were created for each whirl speed run. It contains the number of nodes, runtimes, and iterations for each run of all the whirl speeds. There was a great deal of variation in the total run time of each whirl speed run. In general, as the whirl speed decreased, the time to reach a solution increased. This is illustrated in Figure 3. As stated before, the Turbulent Method increased the solution time, but produces converged solutions that the Node Increase Method cannot converge. One mesh was created for each eccentricity study, and was used for both the turbulent runs. It contains the number of nodes, runtimes, and iterations for each of the eccentricities. With the exception of the 0.1 eccentricity ratio case, increasing the eccentricity ratio increased the time to converge to a solution. Figure 4 shows the time to converge to a solution for each case.

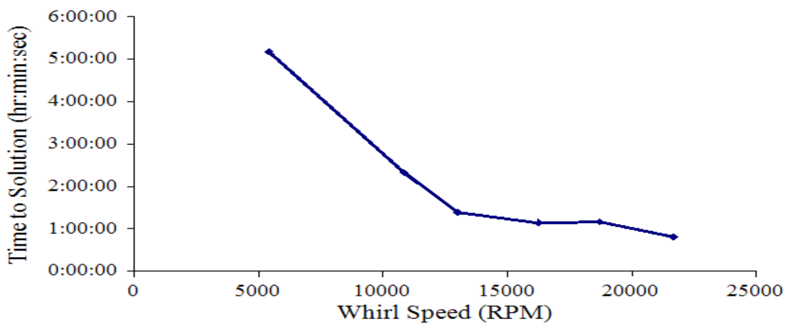


Figure 3. Solution Time VS Whirl Speed

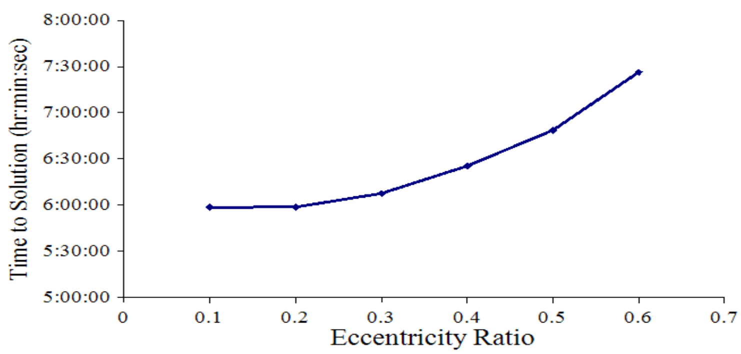


Figure 4. Solution Time VS Eccentricity Ratio

The forces on the rotor were calculated from data exported from CFD. The geometry was aligned so that the force in the x-direction was the axial force[8], the force in the y-direction is the radial force, and the force in the z-direction is the tangential force. The force components are found as in Equation 8:

$$F_X = P * A_X$$
$$F_Y = P * A_Y \tag{8}$$
$$F_Z = P * A_Z$$

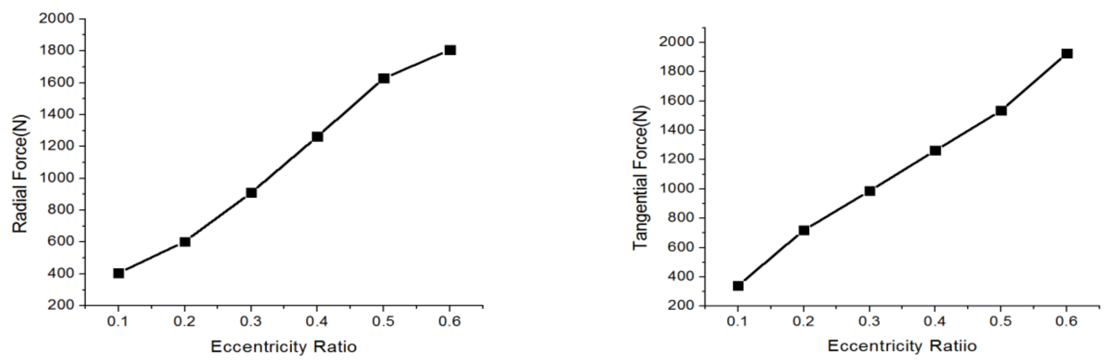
The components of A are shown in Equation (9):

$$A_X = A * n_X$$
$$A_Y = A * n_Y \quad (9)$$
$$A_Z = A * n_Z$$

As was stated earlier, the force in the y-direction corresponds to the force in the radial direction, and the force in the z-direction corresponds to the force in the tangential direction. Another seal characteristic is the effective cross-coupled stiffness, Qe, as shown in Equation (10):

$$Q_e = k - C\omega_{Ncr} \quad (10)$$

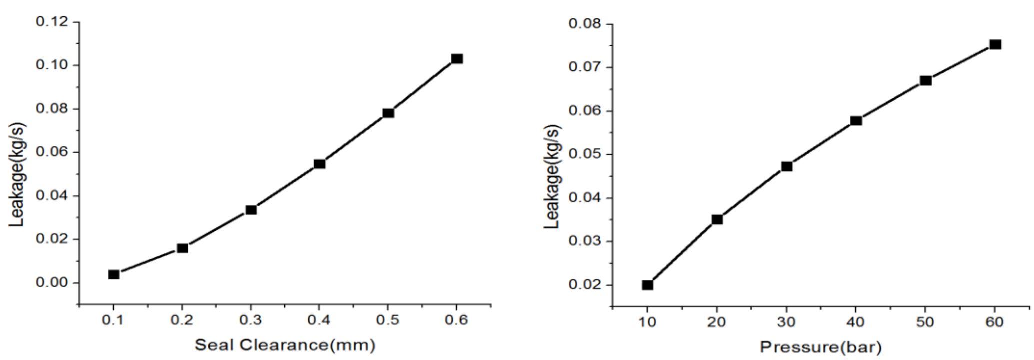
The forces are calculated from the data export from CFD. Figure 5 shows the impact of eccentricity ratio on hydraulic force, hydraulic radial force will increase from 406N to 1806N when the eccentricity radio increase from 0.1mm to 0.6mm in Figure 5 (a). From the Figure 5 (b), it shows that the impact of eccentricity ratio on hydraulic tangential force, hydraulic tangential force will increase from 341N to 1925N when the eccentricity radio increase from 0.1mm to0.6mm.



(a) Radial Force VS Eccentricity Ratio (b) Tangential Force VS Eccentricity Ratio

Figure 5. The Impact of Eccentricity Ratio on Hydraulic Force

The relationships between the eccentricity ratio and pressure [9] on leakage are shown in Figure 6 respectively. Figure 6 (a) show leakage will increase as seal clearance increase. Figure 6 (b) show leakage will increase as pressure increase.



(a) Seal Clearance VS Leakage (b) Pressure VS Leakage

Figure 6. The Impact of Eccentricity Ratio and Pressure on Leakage

A study was performed to investigate the relationship between increasing eccentricity in a seal and the forces produced. The forces were examined for eccentricity ratios from 0.1 to 0.6. There was little variation in the inlet pressures and inlet swirl in each case. The circumferential pressure and velocity distributions were shown to be fourth order polynomials. The dynamic coefficients were found for each eccentricity ratio and are show in Table 1.

Table 1. Dynamic Coefficients for Varying Eccentricity Ratios

Eccentricity Ratio	Direct Stiffness (N/m)	Cross-coupled Stiffness (N/m)	Direct Damping (N-s/m)	Cross-Coupled Damping (N-s/m)	Effective Stiffness (N/m)
0.1	-4.68E+06	3.65E+06	2.35E+03	-8.45E-02	1.89E+06
0.2	-2.78E+06	3.52E+06	1.85E+03	-1.26E-01	2.02E+06
0.3	-2.56E+06	3.07E+06	1.67E+03	-1.42E-01	2.46E+06
0.4	-2.34E+06	2.25E+06	1.32E+03	-1.59E-01	2.78E+06
0.5	-2.23E+06	1.83E+06	9.65E+02	-1.90E-01	3.25E+06
0.6	-1.91E+06	1.60E+06	8.62E+02	-1.75E-01	4.58E+06

It was shown that the radial forces behave linearly with respect to eccentricity ratio. The dynamics coefficients were shown to behave linearly with respect to eccentricity ratio. It was suggested the nonlinearity may occur due to the fluctuation of inlet swirl in each case. This suggestion came about because it was shown that there is a relationship between the normalized dynamics coefficients and the inverse of the normalized inlet swirl for each eccentricity.

4. Conclusion

Nonlinear hydraulic dynamics seal model and CFD model are built in this paper, the impact law of hydraulic pressure distributed, impact of eccentricity ratio on hydraulic force, impact of eccentricity ratio and pressure on leakage. The following conclusions: There is no pressure change in the tooth cavity, but it has a great pressure drop when the stream flow the tooth clearance by the CFD analysis. By solving nonlinear hydraulic dynamics seal model, it can get radial force and tangential force will increase as the eccentricity increase, and leakage will increase with the seal clearance and pressure.

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