An Approach to Determine the Stable Operating Area for Internal Gear Motors and Pumps Based on Safe Lubrication Oil Film Thickness

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Abstract

Designers and manufacturers always desire a simple method to verify the stable and unstable operating area for rotating machines at the early design stage. However, it is sometimes not easy due to lots of phenomena happened inside machines. This paper proposes an approach to determine the instability threshold for the internal gear motors and pumps based on the safe film thickness. By using the mobility method, the maximum eccentricity and the minimum oil lubrication film thickness can be determined, consequently, the minimum speed limit can be retrieved. From that, the stable operating area of internal gear motor and pump can be determined based on the lower speed limit. With proposal approach, the effect of geometry parameters on the stable operating area can be easily assessed. The numerical calculations of stable operating area are also compared to the experimental results of the stable operating area according to the manufacturer. The results show that the geometric parameters, e.g. radial clearance and L/D ratio, have significant effects on stable operating of the internal gear motors and pumps. These parameters, therefore, must be chosen correctly at the early design stage otherwise the stable operating area will be greatly reduced.

Keywords: Stable operating area, Minimum speed limit, Internal gear motor and pump, Lubrication oil film.

1. Introduction

Internal gear motor and pump (IGMaP) is one of the most common types of motors and pumps. It is considered as the "heart" of hydraulic system which is used widely in almost hydraulic fluid power applications e.g. industry, mobile machinery, etc. This is because it is simple, economical, and easy assembly. The operation of IGMaP effects greatly on the performance of system and machines. For small operating area, it limits the application range of IGMaP in general. The operating area of IGMaP is a set of threshold stability curves which can be defined through the rotating speed limit. In reality, in order to verify the operating area for IGMaP, the manufacturers have to perform lots of experiment.

A large number of studies relating to IGMaP have been carried out so far. One of the interesting topics concerning to IGMaP is the pressure and flow pulsation [1-3]. Determination of the internal friction moment inside IGMaP is also performed by some reseaches such as Inaguma [4] in 2006 and Paszota [5] in 2010. In addition, the efficiency of IGMaP is also attracted researchers such as Inaguma [6, 7] in 2013, Song [8] and Khalid [9] in 2016. The sound levels caused by gear motors and pumps are also received great attention from the manufacturers as well as the researchers e.g., Paffoni [10] in 2003, Casoli [11] in 2005 or Mao [12] in 2012.

The instability is an unwanted phenomenon because it can cause the solid contact between the rotor and stator. Ahmad [13], in 2010, performed a survey for the rotor contact phenomenon in rotor dynamics. He pointed out that some main parameters effect on the rotor stability such as stiffness, damping, preload and acceleration of rotor. In the study [14] in 2017 and [15] in 2018, lots of experiments for IGMaP were conducted by Pham. He pointed out that the solid contact between the rotor and stator was found when instability was occurred for both cases: at high pressure and low speed and low pressure and high speed conditions.

Up to now, lots of studies relating to IGMaP have been released. All of them only concerned the "outside" resulting parameter or process of the gear pump, e.g., pressure and flow pulsation, efficiency, noise, or frictional moment. However, studies regarding to determine the operating area for IGMaP have been not released. The reason is that in order to analyze the stability of the IGMaP under the different operating condition, it requires a mathematical model that faithfully describes the dynamic behavior. Meanwhile, there is lots of phenomenon happened inside IGMaP such as the development of the internal friction, axial and radial movement of the ring gear and pressure distribution. It makes the building of an

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accurate mathematical model is complex. Therefore, determination of the stable as well as unstable operating area for IGMaP is now still a challenge for the pump and motor manufacturers. In reality, in order to verify the stable and unstable operating area for IGMaP, the motor and pump manufacturers have to perform lots of experiments to determine the lower speed limit. Consequently, the stable and unstable operating area can be retrieved. It will take time and cost. Moreover, it can be performed only after IGMaP has been manufactured. A simple approach which can check the stability of IGMaP at early design stage will make sense in this case.

The popular method used by lots of researchers [16-20] to study the lower speed limit for rotating machines is based on the transition point of the Stribeck curve. The transition speed is defined through the coefficient of friction. When the friction coefficient passed through a minimum value which is known as the transition point from hydrodynamic to mixed lubrication. It is also known as stable lubrication and unstable lubrication. And as the results, the speed at this transition point is also called the transition speed. The curve of speed limit is considered as the threshold stability which separates the operating area into two areas, i.e., stable and unstable operating areas. The theoretical determination of transition speed is sometimes not easy. Particularly, in case of lots phenomena happened inside the machines likely the internal gear motor and pump. A proposal approach will be introduced in this paper, i.e., safe film thickness based on the calculation of the ring gear orbit. From that, the stable operating area of internal gear motor and pump can be defined based on the lower speed limit. It provides an easy and quickly - to - check the stability of IGMaP at the early design stage. It will save time and cost.

2. System model

Three mains parts of an internal gear motor and pump are described in Fig.1. IGMaP operates based on the meshing between an outer ring gear (rotor) and a fixed driving gear.

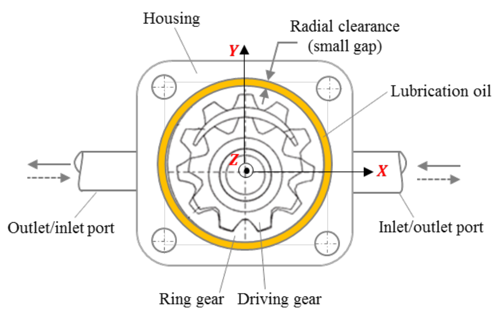

Fig. 1. Cross section of the internal gear motor.

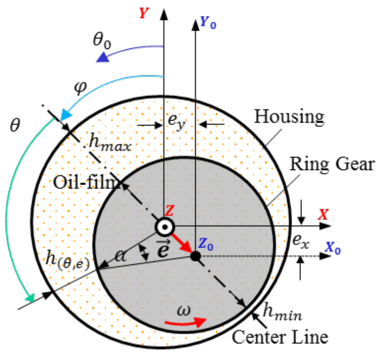

Fig. 2. Oil film thickness.

According to Pham [15], the stability of IGMaP is mostly determined by the stability of the ring gear. The stability of the ring gear will be defined via the lower speed limit.

Stability based on the safe film thickness

The idea is that if the minimum film thickness is larger than the safe film thickness, in other words, the eccentricity of the ring gear is smaller than the permissible eccentricity, the ring gear will be stable, and vice versa. According to Hamrock [17], the safe value for the film thickness should be at least (1.0-1.5) x 2.5 µm. In this study, the safe value for the film thickness is taken at the level of 4 µm. The stability of the internal gear motor/pump is analyzed for two cases, i.e., the aligned ring gear and the misaligned ring gear. The criterion for the stability condition is defined as follows.

Stability condition for the aligned case: In perfect condition, the ring gear is aligned during operation. Safe film thickness condition is as follows:

$$\left[h_a\right] = c - e_{\max} \geq 4\,(\mu\text{m}) \tag{1}$$

Or permissible centricity condition:

$$\varepsilon \leq \left[\varepsilon_a\right] \text{ with } \left[\varepsilon_a\right] = \frac{c-4}{c} \tag{2}$$

Stability condition for the misaligned case: In reality, although the IGMaP is well manufactured, it always exists the misaligned angle (D_m) of the ring gear during operating. Lots of factors can contribute to the misalignment for the ring gear inside the housing of IGMaP [15]. Therefore, the misalignment of the ring gear must be considered under real operating condition. However, theoretical determination of the misaligned angle of the ring gear inside IMGaP is complex. It is only determined through experiment so far. The condition for stability of ring gear in this case is as follows:

Safe film thickness condition:

$$\left[h_m\right] = c - e_{\max} - D_m c \geq 4\ (\mu\text{m}) \qquad (3)$$

Or permissible centricity condition:

$$\varepsilon \leq \left[\varepsilon_m\right] \text{ with } \left[\varepsilon_a\right] = \frac{c - D_m c - 4}{c} \qquad (4)$$

The misaligned angle (D_m) of the ring gear can be taken from experimental data in study [15]. To avoid the solid contact between the ring gear and housing, the real film thickness must be larger than the safe film thickness according to Eq (2). Therefore, if the eccentricity can be calculated then the stability of IGMaP can be determined.

Analysis of the ring gear orbit and computational flow chart for determination of minimum speed limit:

As stated above that if the eccentricity is known, it is able to analysis the ring gear stability by using the safe film thickness condition. In other words, it can be determined the minimum speed limit. From that the stable and unstable operating area for IGMaP can be verified. However, calculation of the eccentricity of the ring gear, particularly under the dynamic loaded on the ring gear, is complex. We have to solve firstly the Reynold's equation to get the pressure distribution in the oil film. Meanwhile, the eccentricity is a function of all geometric and working parameters. Until now, there is no method is released for predicting of the ring gear orbit. Fortunately, by comparing lots of simulation and experiments, Pham in study [22, 23] pointed out that it is able to apply the mobility method to predict the ring gear orbit as well as to calculate the eccentricity. In the following section, the mobility is then integrated into calculation process to complete the stability analysis for IGMaP, e.g., in order to analysis the IGMaP stability, the eccentricity of the ring gear is calculated by using the mobility method. The numerical steps are as follows:

(i.) Make initial condition for eccentricity, attitude angle;

(ii.) Determine the position of the ring gear center corresponding to the initial condition;

(iii.) Calculate the mobility data: the auxiliary mobility vectors and the mobility components;

(iv.) Compute the ring gear velocity components from the mobility data;

(v.) Using the Euler integration method to obtain ε and φ for the next time step;

(vi.) Update the time available, repeat steps *(ii)-(v)* until the final time.

(vii.) Calculation of the minimum film thickness h_{min}

(viii.) Check the stability condition based on the safe film thickness;

(ix.) Update the speed available, repeat calculation of eccentricity until satisfy the safe film thickness condition;

(x.) Calculation of minimum speed limit.

(xi.) Repeat the calculation process for other values of the working pressure.

Table 1. Information of the simulation time.

Parameters	Value	Unit
Initial eccentricity	0.0	-
Initial attitude angle	0.0	rad
Initial time simulation	0.0000	s
Final time simulation	0.0050	s
Integration time simulation	0.0001	s

With the help of mobility method, the eccentricity and the minimum film thickness are calculated. In order to define the minimum speed limit, for each level of the pressure the speed will be reduced from the maximum value until the minimum film thickness is equal to the safe film thickness. At which, the minimum speed limit will be defined.

The internal gear motor and pump type QXM53 of Bucher manufacturer [24] which can operate in 4-quadrant operation is used in calculation. The operating conditions are as follows:

Table 2. Characteristics of IGMaP.

Parameters	Value
The *L/D* ratio	0.28
Displacement effective	50.3 cm³/rev
Max. pressure	200 bar
Max. rotating speed	3000 rpm
Radial clearance	55 μm
Working oil	HLP 46
Oil temperature	40°C
Oil viscosity	0.0402 Pa.s

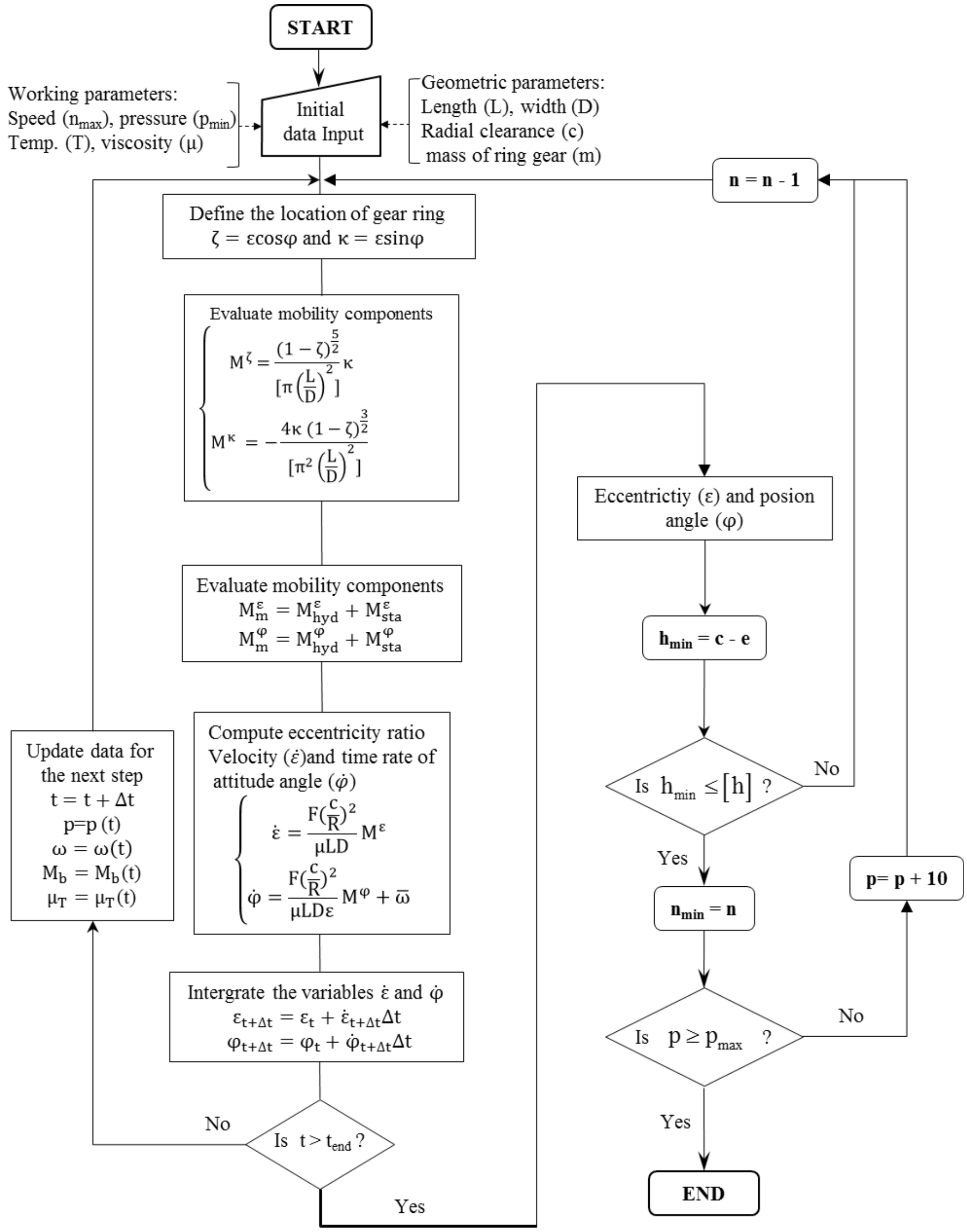

Fig. 3. Computational flow chart for calculation of minimum speed limit.

3. Results and Discussion

3.1. Comparison of numerical and experimental results

The minimum speed limit is then compared to the experimental results according to the manufacturer [24] as presented in Fig. 4. The effect of the misalignment on the stability of the internal gear motor/pump is investigated by using the modification mobility method. The results in study [20] point out that the effect of the misalignment (D_m) is up to 18%. This value will be taken in order to calculate the lower speed limit in case of misalignment. Figure 4 shows that the lower speed limit varies at the different working points. The lower speed limit increases with the increase of the working pressure, meaning that it reduces the stable area of IGMaP. This can be explained by increasing of the working pressure which produces more applied force acting upon the ring gear, therefore the eccentricity increases, resulting in the area of stability will be reduced.

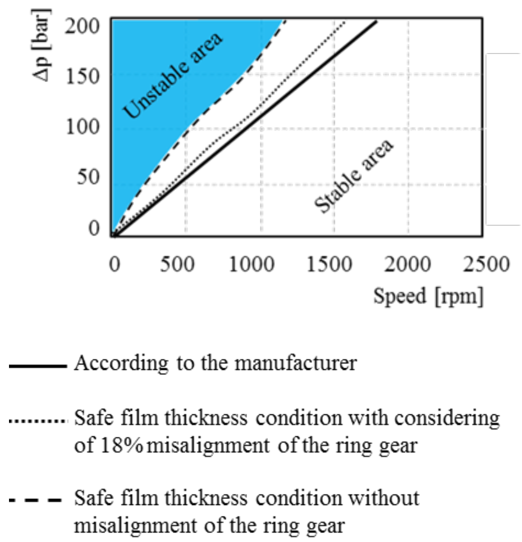

Fig. 4. Stable operating area based on lower speed limit (minimum speed).

Table 3. Comparison of the lower speed limit.

Δp [bar]	The lower speed limit of the internal gear motor/pump [rpm]		
	According to the manufacturer	Using the modification mobility	
		With 18% misalignment	Without misalignment
50	500	400	180
100	950	900	500
150	1350	1250	950
200	1800	1650	1250

The lower speed limit in case of the misalignment agrees well with the lower speed limit given by the manufacturer. Meanwhile, the result for the aligned ring gear points out that the lower speed limit can become further reduced comparing to the misalignment case. This means, without the misalignment the area of stability can be more expansive. The details are presented in Table 3. At the pressure level of 200 bar, one can see that the aligned ring gear causes the lower speed limit to become reduced up to 650 rpm compared to that of misalignment case.

3.2 The effect of the geometry parameters on the stability

Two of the most important design parameters for the internal gear motor/pump are the clearance and the length and Diameter (*L/D*) ratio. Both of them have significant effect on the stability. Investigation of the effect of the clearance and the *L/D* ration on the stability is performed by using the modification mobility method. The instability thresholds are found and presented in Fig. 5 and Fig. 6.

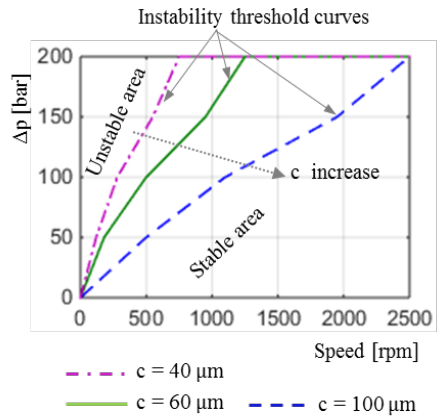

Fig. 5. Instability threshold for various values of the clearance.

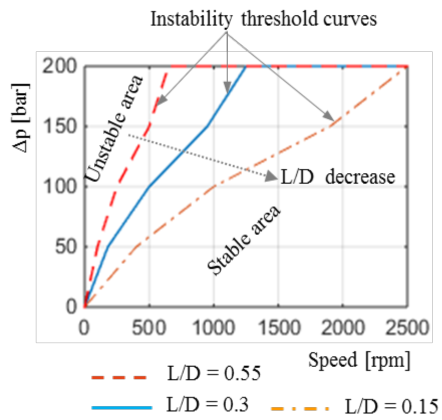

Fig. 6. Instability threshold for different values of L/D ratio.

Figure. 5 presents the effect of the clearance on the stability of the internal gear motor/pump. The instability threshold divides the working area into two areas, namely, a stable and an unstable area. As the clearance increases, the instability threshold shifts towards the stable area, meaning that increasing the clearance increases the area of instability. The results indicate that for the low values of the clearance larger areas of stability are produced than for the large values of the clearance. For the pressure value of 200 bar, the lower speed limit can furthermore reduce 1750 rpm when the value of clearance decreases from value of $100\,\mu m$ to $40\,\mu m$. The effect of the L/D ratio on the stability is described in Fig. 6. The results show that decreasing the L/D ratio reduces the area of stability. For the large value of the L/D ratio, a larger area of stability is yielded than for the low values of the L/D ratio. For the pressure value of 200 bar, then the lower speed limit can furthermore reduce 1850 rpm when the value of L/D ratio increases from value of 0.15 to 0.55. The results point out that the instability threshold speed strongly depends on the L/D ratio and the clearance of the ring gear. From a stability point of view, small values of the clearance and large values of the L/D ratio will be the best for the stability of the internal gear motor/pump, whereas large values of the clearance and small values of the L/D ratio are always the worst. One conclusion from the simulation results is that the clearance and the L/D ratio are two important design parameters regarding to stability of IGMaP. They must be chosen correctly, otherwise the area of stability will be greatly reduced.

4. Conclusion

Based on the results in this work, some following conclusions can be drawn:

- In order to analysis theoretically the stability of IGMaP, we have to calculate firstly the eccentricity. The mobility method is proved itself can predict well the ring gear eccentricity and its orbit. This is the foundation for stability analysis process. Moreover, with the help of mobility method, it is able to compute the maximum eccentricity, or in other words the minimum film thickness, under the different operating conditions. Based on the condition of the safe film thickness, it allows determining the minimum speed limit for IGMaP when it operates in the condition of high pressure and low speed. In addition, if the misalignment angle of the ring gear is considered as an input parameter then it is also able to define the minimum speed limit in case of ring gear misalignment.
- With the completed analysis process as presented in this paper, it provides designers and manufacturers an easy, quickly and simple way to check the effect of geometry and working parameters on IGMaP stability at the early design stage, resulting defining of the overall stable operating for IGMaP. It saves time and cost. From the stability point of view, for small values of radial clearance and large value of the radial force is better for stability of IGMaP.
- Some factors such as the gear meshing between the ring gear and the pinion gear, the effects of the hydrostatic pressure lubrication on the film stiffness and damping or the cavitation phenomenon, should be considered into the calculation in the further study.

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