한국윤활학회지(1996), 제12권 제4호
Journal of KSTLE(1996) Vol. 12, No. 4, pp.13~17

The Error Estimation of Radial Contact Force with a Split Shaft Device for Lip Seals

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스플릿트축장치를 이용한 립실의 접촉력 측정 오차 평가

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요 약—립실의 중요 설계 변수인 접촉력의 측정에는 스플릿트축장치가 흔히 사용된다. 축과 립실의 간섭량은 두 개 스플릿트축의 간격으로서 조절된다. 두 축을 초기 위치로부터 측정하고자 하는 임의 위치로 이동시킬 때 정확한 원을 이루지 못해 측정되는 접촉력은 오차를 포함되게 된다. 본 연구에서는 작은 간섭량 범위 내에서 접촉력을 이론적으로 예측할 수 있는 수식을 유도하고 측정 오차 값을 예측하였다. 측정된 립실의 접촉력은 측정 간섭량이 초기간섭량과 일치하는 경우 외에는 항상 오차를 포함하고 있음을 밝혔다. 이 오차는 작은 간섭량 범위 내에서 립실의 재료 특성이나 형상에 무관하며, 10% 이내의 측정 오차 유지를 위해서는 측정 간섭량이 초기 간섭량의 68%에서 187% 범위 내에 들어야 함을 확인하였다.

Key words—lip seal, radial contact force, split shaft device, interference, measurement error.

1. Introduction

Radial lip seals are one of the most commonly used mechanical elements. Radial lip seals are used to retain oil and to prevent leakage. They are also used to prevent contaminants from entering the lubricant chamber [1, 2].

The advantages of lip seals include low cost, small space requirements, easy installation, and the ability to seal a wide variety of applications. Sealing depends on maintaining adequate lip interface between the elastomeric lip member and the rotating shaft. A schematic of a typical lip seal is shown in Fig. 1.

The sealing function of a lip seal is achieved by the contact between the lip and the shaft. The radial contact force plays an important role in the sealing performance but it should not be given undue emphasis. The contact force must be sufficiently low to prevent the oil film breakdown and subsequent direct wearing rub on the shaft [3].

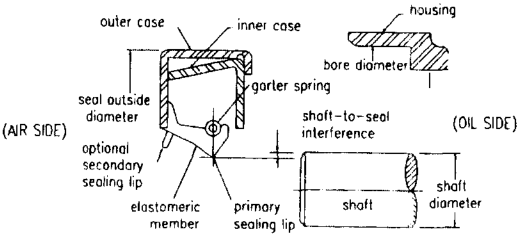


Fig. 1. Typical radial lip seal.

The contact force is generated by the deformation of the lip seal due to the interference and the spring load due to a garter spring. The interference is the gap between the lip seal and the mating shaft. Obviously, the greater the interference the higher the lip pressure or the radial force is. The garter spring load is used to compress the elastomer and produces a more consistent lip pressure than that which would be produced by the elastomer stretch due to the interference.

Generally, a split shaft device is used to measure the radial force of the lip seal. SAE Recommended Practice defines the radial force of a lip seal [4].

Also, the principle of radial force measurement is described and the types of radial force measuring devices are discussed. Although most researchers who have studied the performance of lip seals have used a split shaft device, the measured radial force includes some inevitable error.

As the interference to be measured is far from the initial interference, the measurement error is increased. The initial interference is defined by the difference between the diameter of the undeformed lip seal and the diameter of the mating shaft. The error in split shaft devices is caused by the fact that the split shaft cannot maintain a perfect circle when the interference becomes larger or smaller than an initial value.

In this study, the radial contact force was calculated, and the expected measurement error is estimated. The appropriate ranges of interference to preserve small errors are suggested.

2. Radial Contact Force Calculation

The radial force of a lip seal is defined as the load that the lip seal exerts on the shaft. This force is the sum of the central acting forces around the lip. The radial force is generated by the garter spring and the interference fit. The sealing force can be determined by summing the stresses on the lip. These include the hoop stress created by stretching of the lip and the beam force created by radial deflection of the lip seal.

There are various methods to calculate the radial force [5, 6]. Finite element analysis is used to determine the total contact force and the underlip pressure distribution. The experimental results of radial forces are required to estimate the seal performance and verify the mathematical models. The majority of device uses for obtaining radial force measurement utilize the split shaft device [1, 4].

Fig. 2 illustrates the principle of the split shaft device. A radial lip seal exerts an incremental radial force *p*, expressed in appropriate force per unit of shaft circumference. The force components perpendicular to the split are balanced by force *F*, which the instrument actually measures. This force *F* when multiplied by π is called the total radial force of a seal *P*.

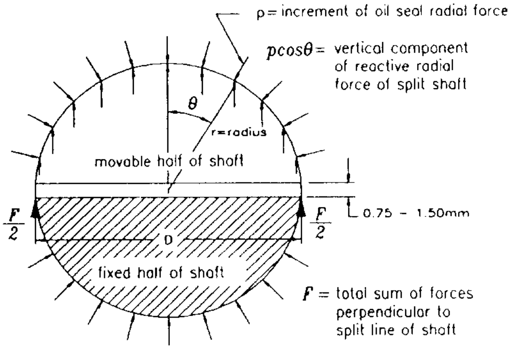


Fig. 2. Principle of the split shaft device.

The gap between each half shaft should be 0.75~1.50 mm to prevent the two halves from exerting a force on each other. And this gap is considered small enough not to affect the measurement [4].

The contact force calculations are given by;

$$F = 2\int_0^{\pi/2} (p\cos\theta)\cdot r\,d\theta = 2pr = pD \tag{1}$$

$$P = (2\pi r)p = \pi F \tag{2}$$

where p is the radial force per unit of circumference, *F* is the measured force by the device, *D* is the shaft diameter, *r* is the shaft radius, *P* is the total radial force, and θ is the angle from the center of the shaft to any point on the shaft surface.

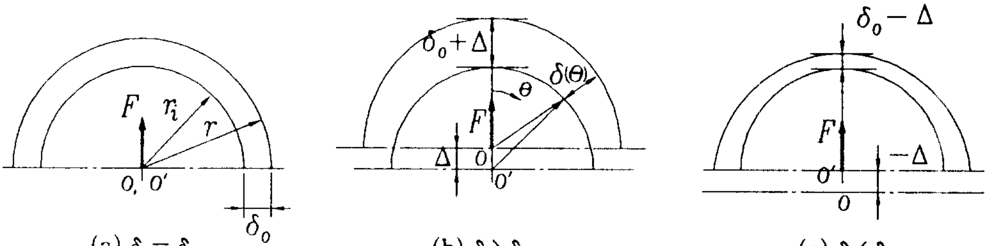
According to many results about the contact force of the lip seal, it is known that the contact force varies linearly with the amplitude of interference [5, 6]. The varieties of shaft diameter are the same meanings as the varieties of interference and the varieties of deflection of the lip seal. From these and the properties of the elastomeric material of the lip seal within the moderate deflection ranges, the radial force at any circumferential location can be expressed as;

$$p(\theta) = k\cdot\delta(\theta) \tag{3}$$

where $\delta(\theta)$ is the radial deformation of the lip seal at θ, and k is the radial stiffness of the lip seal per unit of circumferential locations, which can be assumed to be constant at any circumferential location. Therefore,

$$F = 2\int_0^{\pi/2} k\cdot\delta(\theta)\cos(\theta)\cdot r\,d\theta \tag{4}$$

If $\delta(\theta)$ is constant, equation (4) is equal to equation (1).



(a) $\delta_i=\delta_o$ (b) $\delta_i>\delta_o$ (c) $\delta_i<\delta_o$

Fig. 3. Some cases of the interference to be measured.

A half shaft must be moved to the required position to measure the contact force. When a half shaft is moved from an initial interference position to the desired position, the circumferential contour of the two split shafts will not maintain a perfect circle. And the lip seal will have a nonuniform circumferential deformation pattern. Fig. 3 illustrates each case of interference.

When the radial interference to be measured, δ_i is $(\delta_o+\Delta)$, the deformation of the seal at any circumferential location is calculated as follows.

$$\delta_o=(r-r_i) \tag{5}$$

$$\delta(\theta)=r-x=(r_i+\delta_o)-x \tag{6}$$

where δ_o is the initial radial interference, x is the distance from the center of the shaft to the location of the undeformed seal lip at θ, r_i is the undeformed lip seal radius, and Δ is the distance between the centers of the shaft and the lip seal.

From trigonometry the following relationship can be obtained.

$$(x\cos\theta+\Delta)^2+x^2\sin^2\theta=r_i^2 \tag{7}$$

Because Δ is smaller than x and r_i, Δ^2 can be neglected. Therefore, the approximate solution of x can be obtained.

$$x=r_i-\Delta\cos\theta \tag{8}$$

$$\delta(\theta)=\delta_o+\Delta\cos\theta \tag{9}$$

From equations (4) and (9), the predicted contact force F_m with the split shaft device can be calculated by next equation.

$$F_m=\int_0^{\pi/2}k(\delta_o+\Delta\cos\theta)\cos\theta\cdot r\,d\theta$$
$$=2kr(\delta_o+\frac{\pi}{4}\Delta) \tag{10}$$

When the interference is $(\delta_o+\Delta)$, the exact contact force F_e can be calculated by the next equation.

$$F_e=2\int_0^{\pi/2}(\delta_o+\Delta)k\cos\theta\cdot r\,d\theta$$
$$=2kr(\delta_o+\Delta) \tag{11}$$

When the interference is smaller than initial interference, F_e and F_m are able to be calculated by substituting $-\Delta$ for Δ.

The error between the exact contact force and the measured predicted contact force is given in the next equation.

$$Error=\frac{(F_e-F_m)}{F_e}=\frac{0.2146\Delta}{\delta_o+\Delta}=\frac{0.2146(\delta_i-\delta_o)}{\delta_i} \tag{12}$$

3. Results and Discussion

The measured contact force F_m with the split shaft device and the exact contact force F_e at the same interference were evaluated by assuming that the radial stiffness of the lip seal is constant, and that the interference is much smaller than the shaft radius. Equation (12) provides the error between F_m and F_e.

Table 1 contains the measurement errors for various interference to be measured and the distance between the centers of the shaft and the lip seal. Fig. 4 illustrates the interference as a function of the distance between the centers of the shaft and the lip seal. Fig. 5 illustrates the measurement errors for the distance between the centers of the shaft and the lip seal. Fig. 6 illustrates the exact contact force and the measured contact force as a function of the radial interference. Fig. 7 illustrates the error which depends upon the radial interference.

It has been found that there are differences between F_m and F_e in all cases except when the initial interference is equal to the interference to be

Table 1. Measurement errors for the interference to be measured and the distance between the centers of the shaft and the lip seal

interference to be measured (δ_i)	distance between the centers of the shaft and the lip seal (Δ)	measurement errors (%)
0	-1.00 δ_0	-
0.25 δ_0	-0.75 δ_0	-64.4
0.50 δ_0	-0.50 δ_0	-21.5
0.75 δ_0	-0.25 δ_0	-7.2
1.00 δ_0	0	0
1.25 δ_0	0.25 δ_0	4.3
1.50 δ_0	0.50 δ_0	7.2
1.75 δ_0	0.75 δ_0	9.2
2.00 δ_0	1.00 δ_0	10.7
3.50 δ_0	2.50 δ_0	15.3
6.00 δ_0	5.00 δ_0	17.9
11.00 δ_0	10.00 δ_0	19.5

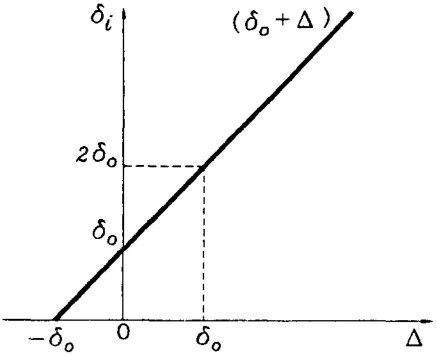


Fig. 4. Interference as a function of the distance between the centers of the shaft and the lip seal.

measured. These errors are dependent upon the initial interference and the distance between the centers of the shaft and the lip seal. These errors change from minus infinite when Δ is $-\delta_i$ to the converged value 0.215 when Δ is infinite.

As the radial stiffness of the lip seal is able to be assumed as constant, errors are not affected by the radial stiffness of the lip seal. This assumption under the small various range of the interference has been verified by the previous results [5, 6]. The results indicate that the errors are not dependent upon the material properties and the shape of the lip seal, but rather dependent upon the amplitude of the initial interference and the interference to be measured. When the lip seal contains a garter spring, the initial interference becomes larger than when it does not have a garter spring. So the errors will decrease a little in comparison with when it does not have a garter spring.

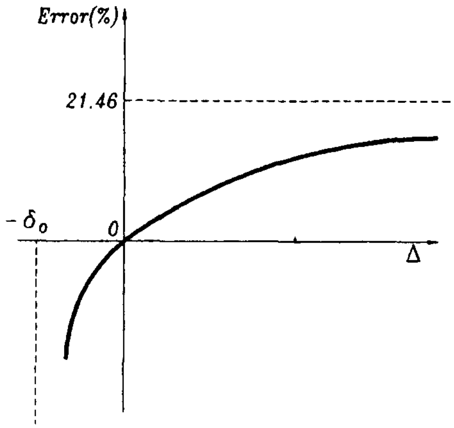


Fig. 5. Error vs. the distance between the centers of the shaft and the lip seal

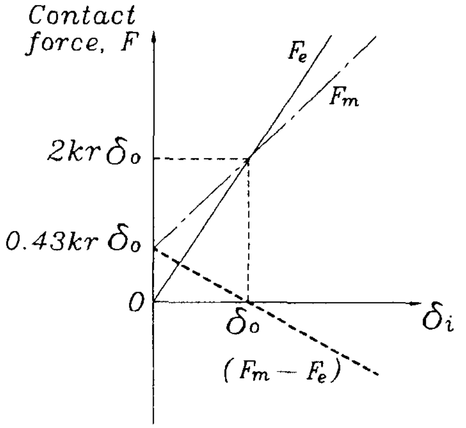


Fig. 6. The exact and the measured contact forces as a fuction the interference.

In order to keep the measurement error within 5% with the split shaft device, the distance must be ranged -0.19 $\delta_o<\Delta<0.30\ \delta_o$ and the feasible interference to be measured must be ranged 0.81 $\delta_o < \delta_i < 1.30\delta_o$. In order to keep within 10%, this value must be -0.32 $\delta_o < \Delta < 0.87\delta_o$ and 0.68 $\delta_o < \delta_i < 1.87\delta_o$. When the interference to be measured is larger than the initial interference, the exact contact force is always larger than the measured contact force. This means that the contact

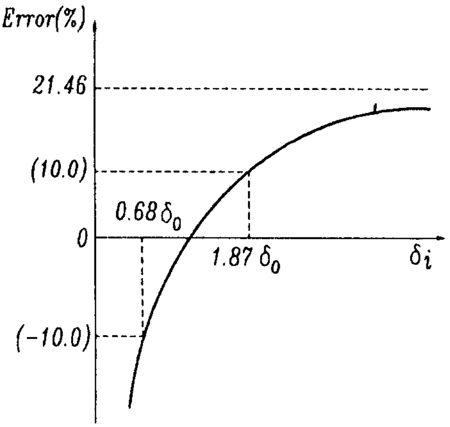


Fig. 7 Error as a function of the interference.

force has been underestimated. When the interference to be measured is smaller than the initial interference, the exact contact force is always smaller than the measured contact force. This means that the contact force has been overestimated.

4. Conclusions

The measurement error of the radial contact force with the split shaft device for the lip seal has been estimated. An explicit equation for the measurement error as a function of the initial interference and the interference to be measured was developed. The following conclusions can be drawn from the results of this study.

1. The measured contact force of the lip seal includes the measurement error in all cases except when the initial interference is equal to the interference to be measured.
2. This error when the interference is small is not dependent upon the material properties and the shape of the lip seal, but rather dependent upon the amplitude of the initial interference and the interference to be measured.
3. When the interference to be measured is larger than the initial interference, the measured contact force is always underestimated. When the interference to be measured is smaller than the initial interference, the measured contact force is always overestimated.
4. In order to keep the measurement error within 10%, the interference to be measured must range between (0.68 × initial interference) and (1.87 × initial interference).

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