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Kinetic friction characterizations of the tubular rubber seals

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ABSTRACT

In this paper, both the kinetic friction characterizations and the stick–slip motion phenomena for the tubular rubber seals are studied. First, the kinetic friction model of the rubber seal is established to explain the kinetic friction mechanism of the tubular rubber seals. Second, both the measurement principle and the test instrument for the kinetic friction properties of the tubular rubber seals are developed, and then both the normal force curve and the friction force curve are obtained. Finally, the influences of the sliding velocity and the compressive displacement on the kinetic friction properties and the stick–slip motion of the tubular rubber seals are analyzed. The results will play an important role for designing and evaluating advanced rubber seal components.

1. Introduction

Tubular rubber components have important applications in many seal structures such as airplane door, temperature chamber door, car door, etc. In fact, the kinetic friction behaviors of the rubber seals depend on the ambient temperature, the applied load, the sliding history, the substrate roughness, the physical properties and the geometrical configurations of the rubber seals. Also, the stick–slip motion is a common phenomenon in rubber friction which affects the applicability of the rubber seal components. Therefore, it is important to study the kinetic friction characterizations and the stick–slip motion behaviors of the rubber seals for evaluating and designing advanced rubber seal materials.

Some research works on the stick–slip motion in rubber frictions have been reported. Persson et al. [1–3] systematically studied both the kinetic friction characterizations and the friction mechanisms of the rubber materials, including the friction theory between rubber and hard/rough substrate which depends on the substrate surface roughness and the sliding velocity [1]; the differences between the static friction and the kinetic friction under the creep condition by means of Molecular Dynamics (MD) simulations [2]; and the rubber friction law to simulate the anti-blocking system braking of the tire body [3]. Barquins et al. [4] studied the influences of the sliding speed, the ambient temperature, the normal load and the contact geometry on the rubber friction. Lorenz et al. developed a theoretical model which divides the frictional force into three parts to study the influencing factors of the friction performance [5], and investigated the influence of the velocity and the temperature on the friction behavior of the tire [6]. Motchongom-Tingue et al. [7] studied the stick–slip motion of the nonsinusoidal substrate by means of the model of two spring-blocks system; Degrange et al. [8] analyzed the tribological behaviors of two rubbers using thermo-mechanical models and tribological experiments; and Scheibert et al. [9] studied the friction-induced torque at the interface controlling the periodic stick–slip motion. However, the kinetic friction of the tubular rubber seal is still a difficult research topic due to the lack of the specific measurement machine and the theoretical solution.

In this paper, the simplified theoretical model is established to analyze the kinetic friction characterization of the tubular rubber seal. The measurement principles of the tubular rubber seal component are developed and the stick–slip behaviors of the tubular rubber seals are studied experimentally for different sliding velocities and various compressive displacements. Also, the dynamic friction mechanisms of the tubular rubber seals are discussed.

2. Theoretical model of stick–slip motion

The stick–slip motion in rubber friction attributes to the alternative variation between the kinetic friction and the static friction [10,11]. A simplified model in rubber friction is established to explain the stick–slip phenomenon as shown in Fig. 1. Here, the block rubber seal with the size $l \times h \times d$ in length × width × thickness is considered, which is fixed on the basement board. The loading board moves on the rubber seal at a constant velocity v_0, and the velocity of the basement board is considered to be zero. The geometrical shape of the rubber seal is changed due to the static friction force F_s which can be described by the deformation

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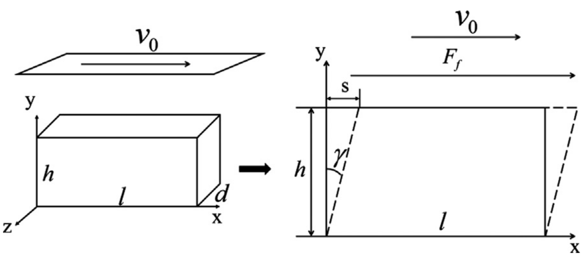

Fig. 1. The simplified friction model of the rubber seal.

angle γ. Also the displacement s of the rubber seal surface can be expressed as $s=\gamma h$. So the velocity v_r of the rubber surface can be expressed as $v_r=\dot{s}=\dot{\gamma}h$. The relationship between the static friction force F_s and the deformation angle γ of the rubber seal is expressed as $F_s=\gamma Gl$ when the rubber seal surface moves along with the loading board at the same velocity v_0, where G is the shear modulus of the rubber. However, if the cross section of the rubber seal is of other geometrical configurations, the relationship between the static friction force F_s and the deformation angle γ should satisfy $F_s=\gamma H$, where the coefficient H is related to the shear modulus G of the rubber and the geometrical shape of the cross section in the rubber seal.

In fact, the loading board slips on the rubber block suddenly in the initial state of the friction movement. During the friction process of the rubber seal, the velocity v_0 of the loading board is larger than the velocity v_r of the rubber surface, which has a relative motion between the surface of the rubber seal and the loading board. With the movement of the loading board, the velocity v_r of the rubber seal surface increases rapidly up to the velocity v_0 of the loading board, but this slipping time is too short to measure by means of the force sensor. So it is assumed that the surface of the rubber seal moves along with the loading board in the beginning of the rubber seal friction for establishing the simplified theoretical model. Therefore, the whole friction processes are mainly divided into the sticking stage and the slipping stage.

The sticking stage begins at first and the rubber block surface moves along with the movement of the loading board. The deformation angle γ, the velocity v_r of the rubber seal surface and the friction force F_f can be expressed as

$$\gamma=\frac{v_0}{h}t_1 \tag{1}$$

$$v_r=\dot{\gamma}h=v_0 \tag{2}$$

$$F_f=F_s=\frac{v_0}{h}t_1 H \tag{3}$$

where t_1 is the time variable in the sticking stage.

The rubber block surface will slip on the loading board in the slipping stage after the friction force F_f is up to the maximum static friction force $\mu_s F_N$. Here μ_s is the maximum static friction coefficient. The governing equation at the slipping stage can be expressed as

$$\gamma H+\dot{\gamma}C-\mu_k F_N=\hat{m}\hat{a} \tag{4}$$

where C is the damping of the rubber seal. μ_k is the kinetic friction coefficient. F_N is the normal force. $\hat{m}$ is the equivalent mass and $\hat{a}$ is the equivalent acceleration. The kinetic friction force F_k can be expressed as $F_k=\mu_k F_N$. The equivalent inertia force $\hat{m}\hat{a}$ can be expressed as

$$\hat{m}\hat{a}=\int_A y a(y)\rho dA \tag{5}$$

here $a(y)$ is the acceleration of the rubber seal and the y axis is in the vertical direction as shown in Fig. 1. ρ is the density of the rubber. A is the cross sectional area. For the block rubber seal, the equivalent inertia force can be further expressed as

$$\hat{m}\hat{a}=-\int_0^h \ddot{\gamma}y\frac{m}{h}dy=-\frac{mh}{2}\ddot{\gamma} \tag{6}$$

where m is the mass of the rubber block. It is obvious that Eq. (6) is just suitable for the case of the rubber block. But the equivalent mass of other shape rubber seals can also be obtained by means of Eq. (5).

Based on Eq. (6), Eq. (4) can be further expressed as

$$\ddot{\gamma}+\frac{2C}{mh}\dot{\gamma}+\frac{2H}{mh}\gamma-\frac{2\mu_k F_N}{mh}=0 \tag{7}$$

The corresponding initial conditions can be expressed as

$$\begin{cases} \gamma|_{t_2=0}=\frac{\mu_s F_N}{H} \\ \dot{\gamma}|_{t_2=0}=\frac{v_0}{h} \end{cases} \tag{8}$$

here t_2 is the time variable in the slipping stage.

So the solution of the governing Eq. (7) is

$$\begin{aligned}\gamma=&\frac{(\mu_s-\mu_k)F_N}{H}\exp\left(-\frac{C}{mh}t_2\right)\cos\left(\frac{1}{2}\sqrt{\frac{8H}{mh}-\frac{4C^2}{m^2h^2}}t_2\right)\\ &+\frac{1}{\sqrt{\frac{8H}{mh}-\frac{4C^2}{m^2h^2}}}\exp\left(-\frac{C}{mh}t_2\right)\left[\frac{2C}{mh}\frac{(\mu_s-\mu_k)F_N}{H}+\frac{2v_0}{h}\right]\sin\left(\frac{1}{2}\sqrt{\frac{8H}{mh}-\frac{4C^2}{m^2h^2}}t_2\right)+\frac{\mu_k F_N}{mh}\end{aligned} \tag{9}$$

Thus both v_r and F_f can be expressed as

$$\begin{aligned}v_r=\dot{\gamma}h=&-\frac{(\mu_s-\mu_k)F_N}{H}\frac{C}{m}\exp\left(-\frac{C}{mh}t_2\right)\cos\left(\frac{1}{2}\sqrt{\frac{8H}{mh}-\frac{4C^2}{m^2h^2}}t_2\right)\\ &-\frac{(\mu_s-\mu_k)F_N h}{H}\exp\left(-\frac{C}{mh}t_2\right)\frac{1}{2}\sqrt{\frac{8H}{mh}-\frac{4C^2}{m^2h^2}}\sin\left(\frac{1}{2}\sqrt{\frac{8H}{mh}-\frac{4C^2}{m^2h^2}}t_2\right)\\ &-\frac{1}{\sqrt{\frac{8H}{mh}-\frac{4C^2}{m^2h^2}}}\frac{C}{m}\exp\left(-\frac{C}{mh}t_2\right)\left[\frac{2C}{mh}\frac{(\mu_s-\mu_k)F_N}{H}+\frac{2v_0}{h}\right]\sin\left(\frac{1}{2}\sqrt{\frac{8H}{mh}-\frac{4C^2}{m^2h^2}}t_2\right)\\ &+\exp\left(-\frac{C}{mh}t_2\right)\left[\frac{2C}{mh}\frac{(\mu_s-\mu_k)F_N}{H}+\frac{2v_0}{h}\right]\frac{h}{2}\cos\left(\frac{1}{2}\sqrt{\frac{8H}{mh}-\frac{4C^2}{m^2h^2}}t_2\right)\end{aligned} \tag{10}$$

$$F_f=F_k=\mu_k F_N \tag{11}$$

Actually, the slipping time of the rubber seal is very short during one stick–slip period without considering the damp of the rubber seal; the energy loss caused by the viscoelasticity of the rubber is ignored in the simplified theoretical analysis. So both γ and v_r can be expressed as

$$\gamma=\sqrt{\frac{mh}{2H}}\frac{v_0}{h}\sin\left(\sqrt{\frac{2H}{mh}}t_2\right)+\frac{(\mu_s-\mu_k)F_N}{H}\cos\left(\sqrt{\frac{2H}{mh}}t_2\right)+\frac{\mu_k F_N}{H} \tag{12}$$

$$v_r=\dot{\gamma}h=v_0\cos\left(\sqrt{\frac{2H}{mh}}t_2\right)-\frac{(\mu_s-\mu_k)F_N}{H}h\sqrt{\frac{2H}{mh}}\sin\left(\sqrt{\frac{2H}{mh}}t_2\right) \tag{13}$$

Obviously, the slipping stage will be finished when v_r is equal to v_0. Then the sticking stage will be repeated after the slipping stage has been finished. Both the sticking stage and the slipping stage form a loop to describe the friction movement of the block rubber seal.

There is no doubt that the above-stated theoretical result is not only suitable for the block rubber seal but also for other shapes of the rubber seals if the relationship between the static friction force and the geometrical deformation of the rubber seal satisfies the assumption: $F_s=\gamma H$ or $F_s=(s/h)H$.