Study on fatigue life model of "goose-neck" type slip ring

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Abstract. In view of the problem that it is difficult to predict the fatigue life of the "goose-neck" type slip ring, through the analysis of the working principle and the movement force of the slip ring, it is found that the main failure mode of the slip ring is the FPC conductor layer fracture, the failure position is at the junction of the FPC (inner ring) and the FPC (goose-neck). The fatigue life prediction model of slip ring is established by energy method, the analysis of the model shows that the fatigue life of slip ring decreases with the increase of the rotation angle of the inner ring, the radius ratio of the slip ring inner ring to the slip ring outer ring and the thickness of FPC conductor layer.

1. Introduction

In order to reduce the influence of the winding torque, the slip ring is usually used to transmit signals and energy in the limited rotation mechanism. At present, the friction torque of the commonly used copper ring-brush type slip ring is in the order of N.m, the copper ring-brush type slip ring has large volume, heavy weight and large interference torque, which cannot meet the requirements of light and miniaturization of rotary structure and long service life. "Goose-neck" type slip ring is mainly composed of inner ring, outer ring and flexible printed circuit board (FPC). The FPC arranged in a rotary way between the inner ring and outer ring is used for signal transmission and power transmission. Its structure is simple, the interference torque is in the order of mN. m, with the characteristics of long service life and low installation accuracy requirements, which can make up for the deficiency of copper ring brush type slip ring.

P.-A. Mäusli put forward a design scheme of slip ring, the inner diameter is 191mm, outer diameter is 310mm, and its torque is 15mN.m, however, this design cannot solve the lag phenomenon caused by cable joint, and there is a key problem of inconsistent forward and reverse torque [1]. Eric D. Miller designed a "goose-neck" type slip ring with a coarse pointing mechanism for laser communication, the test results show that its life is better than 33000 cycles [2]. Yiqun Zhang designed a "goose-neck" type slip ring, the inner diameter is 80mm, the outer diameter is 100mm [3,4], however, it did not study the failure mechanism of the slip ring, did not analyze the factors affecting the service life of the slip ring, just measured the fatigue service life of the slip ring. One of the important parameters to evaluate the performance index of "goose-neck" type slip ring is its service life, the interface of FPC attached to the inner ring (FPC(inner ring)) and FPC attached to the "goose-neck" (FPC(goose-neck)) bears high cycle alternating stress during the reciprocating rotation of the slip ring, even under the condition of ensuring...
the safety of static structure, after a long time of work, the above interface will suffer from fatigue failure, thus affecting the service life of the slip ring. At present, the relevant research work is only to test the fatigue life of "goose-neck" slip ring from the perspective of test, do not to study the failure mechanism and life model of slip ring in depth.

2. Working principle of "goose-neck" type slip ring

The "goose-neck" type limited angle conductive slip ring is composed of inner ring, outer ring, FPC and retaining ring. The inner ring is installed on the shaft, the outer ring is installed on the shaft seat, the two ends of FPC are respectively fixed on the inner and outer ring, thus forming a "goose-neck" between the inner and outer ring. The structural diagram of the slip ring is shown in Figure 1.

![Figure 1. Structural diagram of "goose-neck" type slip ring.](image)

3. Fatigue life prediction model of "goose-neck" type slip ring

When the "goose-neck" type slip ring rotates reciprocally, the FPC between the inner and outer ring bends, the bending radius at the junction of FPC (inner ring) and FPC (goose-neck) is small, with the neutral plane of FPC conductor layer as the boundary, the outward part bears the tension, and the more outward the tension is, the inward part bears the pressure, and the more inward the extrusion is, as shown in Figure 2. After the action of high cycle alternating load for a long time, FPC is prone to produce tiny cracks at the stress concentration part of the internal and external surfaces, with the increase of the action time of load, the cracks begin to expand until the fracture failure, resulting in the distortion of FPC transmission signal and even the inability to transmit signal, which ultimately affects the fatigue life of the slip ring.

![Figure 2. Force diagram of FPC during bending.](image)

According to the different bending radius of each part of FPC when it works on the slip ring, it can be divided into three parts: FPC (inner ring), FPC (goose-neck) and FPC attached to the outer ring (FPC...
(outer ring)). The bending radius of FPC at these three positions are $r, \frac{R(1-\varepsilon)}{2}$ and $R, \varepsilon = \frac{r}{R}$ is defined as the radius ratio of inner ring to outer ring. At present, the commonly used formula for calculating the minimum bending radius $r_{min}$ of FPC is:

$$r_{min} = \left(\frac{nh}{2} + \frac{(n-1)d}{2}\right)\left[1 - \frac{E_{\varepsilon}}{E_c}\right] - \sigma$$

(1)

where $n, d, h, E_c$, and $\sigma$ represents number of conductive layers, inter-layer medium thickness, thickness of conductor layer, deformation of conductor layer, and thickness of covering film, respectively, these concepts are show in Figure 2.

During the design of slip ring, the position of FPC (inner ring) and FPC (goose-neck) shall meet the minimum bending radius requirements of FPC:

$$r_{min} \leq r \leq R - 2r_{min}$$

(2)

The movement process and stress of the slip ring is shown in Figure 3, the inner ring drives FPC to rotate around the outer ring. $\chi$ and $\chi''$ are the tangent points of FPC (goose-neck) and inner ring before and after the slip ring rotation, respectively, the $\chi''$ point is the same as the point on FPC (goose-neck) before rotation, $\alpha$ represents the rotation angle of the inner ring of the slip ring, which is the same as the rotation angle of the azimuth axis of the turntable, $\beta$ represents the rotation angle of the "goose-neck". It can be seen from the motion relationship of the slip ring that $\beta = \frac{\alpha}{1 + \varepsilon}$. The bending direction, bending radius and bending stress of FPC will change near $\chi$ point, under the action of alternating load, fatigue failure is most likely to occur near the $\chi$ point.

Figure 3. Motion force diagram of slip ring.

The energy release rate of FPC conductor layer $G$ is defined as the energy absorbed by the increase of unit crack length and unit thickness in the process of conductor layer crack propagation, which is directly related to the bending radius of the object in a stable state. $\Gamma_{crystal}$ is defined as the critical fracture energy of FPC conductor layer, which can be determined by experiment [5], its physical meaning is the minimum energy that can make the object fracture. When $G$ is greater than $\Gamma_{crystal}$, it is considered that
FPC conductor layer breaks. The energy release rate of FPC conductor layer $G$ mainly comes from the change of elastic potential energy $G_P$ corresponding to the change of bending radius of FPC during the rotation of slip ring, it can be considered that $G = G_P$. The size of the elastic potential energy of the conductor layer is related to the material of the conductor layer and the degree of the elastic deformation of the conductor layer, when the radius of the outer ring of the slip ring $R$ is fixed, it corresponds to the working form of the slip ring, $G_P$ is related to the bending rigidity of the conductor layer $D$, the rotation angle of the inner ring of the slip ring $\alpha$ and the radius ratio of inner ring to outer ring $\epsilon$. Combined with the movement process of slip ring and the rule of fatigue crack growth, it can be seen that when $R$, $\epsilon$ and the parameters of conductor layer are constant, the crack growth speed is related to the rotation angle of slip ring inner ring $\alpha$, in addition, there is a critical rotation angle $\phi$ and the critical crack growth length of conductor layer $L_\phi$, and $L_\phi = \frac{R \epsilon \phi}{1 + \epsilon}$ is only related to the material of conductor layer, and has nothing to do with $\alpha$ and $\epsilon$. When $0 \leq \alpha \leq \phi$, the closer $\alpha$ is to 0, the slower the crack growth speed is, and the longer the fatigue life of the slip ring $N$ is, the closer $\alpha$ is to $\phi$, the faster crack growth speed is, and the shorter fatigue life of slip ring $N$ is; When $\alpha > \phi$, the crack growth rate will not change with the change of slip ring rotation angle $\alpha$, the crack growth length of conductor layer will not continue to increase when it reaches $L_\phi$, and the fatigue life of slip ring $N$ will maintain a stable value $N_\phi$.

When the inner ring of the slip ring turns $\alpha$ ($0 \leq \alpha \leq \phi$), the change of FPC (inner ring) line length is $r \beta$, the change of bending elastic potential energy of FPC conductor layer $G_P$ is as follows:

$$
G_P = \left| \int \frac{d\theta}{\chi'} \int \frac{D \epsilon \kappa d \kappa}{\epsilon} \right| \left| 0 = \frac{(1 + \epsilon) \cos \phi + \sqrt{(1 + \epsilon)^2 \cos^2 \phi - 4 \epsilon}}{\sin \left( \frac{2 \epsilon \alpha}{1 - \epsilon^2} \right)} \right| \frac{(1 - \epsilon)}{\sin \phi} \quad 0 \leq \alpha \leq \phi
$$

(3)

where $\kappa$, $\theta$, and $\lambda$ represents Curvature of conductor layer element, the angle between $\chi$ point and $\chi'$ point and the straight line connected with the center of the slip ring during the rotation of the inner ring, and the radius of curvature at point $\chi'$.

Combining the relationship between $G_P$ and $\phi$, the solution of formula (3) is as follows:

$$
G_P = \left| \frac{D \phi}{4R \epsilon} - \frac{D \epsilon}{2} \int \frac{4}{R(1 + \epsilon) \cos \theta + R \sqrt{(1 + \epsilon)^2 \cos^2 \theta - 4 \epsilon}} d\theta \right| \quad 0 \leq \alpha \leq \phi
$$

(4)

$$
G_P = \left| \frac{D \phi}{4R \epsilon} - \frac{D \epsilon}{2} \int \frac{4}{R(1 + \epsilon) \cos \theta + R \sqrt{(1 + \epsilon)^2 \cos^2 \theta - 4 \epsilon}} d\theta \right| \quad \alpha > \phi
$$

It is defined that the fatigue fracture life of slip ring is $N$, that is to say, when the slip ring rotates $N$(cycle), the total change of elastic potential energy of conductor layer is $N G_P$, so according to the critical fracture conditions are as follows:

$$
N = \frac{\Gamma_{\text{critical}}}{G_P}
$$

(5)

The fatigue life of slip ring $N$ can be obtained by substituting formula (4) into formula (5).
Through the analysis of the model, we can draw the following conclusions. The fatigue life of the slip ring will be greatly reduced with the increase of the rotation angle of the inner ring, and when it is increased to a certain angle $\varphi$, the life $N$ will tend to a stable value, in general, the critical rotation angle of the slip ring $\varphi$ is small and its working range is larger than $\varphi$. Therefore, when the slip ring design is completed, its fatigue life $N$ is generally a certain value $N_\varphi$. With the increase of the radius ratio of inner ring to outer ring, the fatigue life of the slip ring will decrease and approach a linear change. The "goose neck" type slip ring with long service life can be obtained by reducing the radius ratio of inner ring to outer ring. However, due to the limitation of FPC minimum bending radius and turntable aperture, the $\varepsilon$ value cannot be too small. The fatigue life of the slip ring will decrease with the increase of the thickness of the conductor layer. According to formula (3), when $(\alpha, \varepsilon)$ is fixed, the bending rigidity of the conductor layer $D$ is directly proportional to $G_P$ and inversely proportional to the fatigue life $N$. Copper foil is the most commonly used and economical conductor layer material in the FPC manufacturing process, its elastic modulus $E$ is a fixed value, generally, the smaller rigidity is obtained by reducing the cross-sectional area of the conductor layer. According to the cross-sectional geometry, we can get that

$$D = \frac{Ebh^3}{12},$$

Where $b$ is the width of the conductive layer, the thickness of the conductor layer $h$ has the greatest influence on the life $N$, and the smaller $h$ is, the greater $N$ is. At present, the thickness of the conventional conductor layer is 0.5oz, 1oz, and 2oz, the maximum value is 3oz. Changing the size of $h$ from the material point of view can greatly change the fatigue life of the conductive slip ring $N$, however, $h$ cannot be too small, otherwise it will limit the power on ability of the conductive slip ring.

4. Conclusion
The fracture of FPC conductor layer is the main factor of fatigue failure of "goose-neck" type limited angle conductive slip ring. In order to predict the fatigue life of the slip ring, based on the law of slip ring motion and the energy source of crack growth in the conductor layer, a fatigue life prediction model of the slip ring in the process of reciprocating rotation is established based on the energy method. By means of the control variable method, the influences of the rotation angle of the inner ring, the radius ratio of inner ring to outer ring of the slip ring and the thickness of the conductor layer on the fatigue life of the slip ring are further analyzed, considering the working range of slip ring, the power on ability of FPC and the requirement of minimum bending radius, in general, when the static safety is satisfied, the fatigue life of slip ring can be increased by reducing the radius ratio of inner ring to outer ring of slip ring, and the thickness of conductor layer can be reduced to obtain the slip ring with longer fatigue life when the large optical aperture is needed. Due to the limitation of test conditions, this paper does not test the three factors that affect the fatigue life of slip ring discussed above, which will be made up for in the next study.

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