UDC 629.7.064.5; 629.78.05; 89.25.21
Doi: 10.31772/2712-8970-2024-25-2-190-201

Для цитирования: Гришин А. А. Обеспечение долговечности и надежности контактных колец токосъемных устройств при работе в упруго-пластическом состоянии // Сибирский аэрокосмический журнал. 2024. Т. 25, № 2. С. 190–201. Doi: 10.31772/2712-8970-2024-25-2-190-201.

For citation: Grishin A. A. [Ensuring durability and reliability of contact rings of current collection devices when working in elastic-plastic state]. *Siberian Aerospace Journal.* 2024, Vol. 25, No. 2, P. 190–201. Doi: 10.31772/2712-8970-2024-25-2-190-201.

Обеспечение долговечности и надежности контактных колец токосъемных устройств при работе в упруго-пластическом состоянии

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Надежность работы кольцевых токосъемных устройств в течение заданного срока службы играет определяющую роль в работе систем электропитания различной техники и во многом зависит от прочности и надежности всех его компонентов, в частности, контактных колец. Одной из важнейших характеристик кольцевых токосъемных устройств является сопротивление контакта, уменьшение которого осуществляют путем применения цветных и драгоценных материалов, обладающих низким сопротивлением, с одновременным увеличением прижимной силы между кольцами токосъемника. Такой подход приводит к резкому росту напряжений в контактном кольце, которые могут достигать и даже превышать предел текучести материала, циклически изменяясь по кольцу в процессе вращения кольца с последующим усталостным разрушением.

Однако работоспособность контактных колец в таких тяжелых условиях вполне можно обеспечить в случае малых скоростей движения и небольшого числа циклов нагружения за счет использования области малоцикловой усталости на кривой Веллера. Для этого в данной работе предложены методы аналитического расчета напряженно-деформированного состояния кольца токосъемного устройства, которые позволяют определить уровень действующих напряжений в материале и по кривой Веллера определить допускаемое число циклов нагружения и коэффициент запаса по усталости. Также предложен метод расчета надежности кольца, который позволяет оценивать вероятность безотказной работы и разрушения.

По предложенным методикам выполнены расчеты колец токосъемного устройства, применяемого в космических аппаратах типа «Экспресс», которые показали работоспособность методик и позволили обеспечить требуемый срок службы контактных колец и их надежность. Предложенная аналитическая формулировка методик позволяет решать как проверочные, так и проектировочные расчеты колец в зависимости от поставленной задачи.

Ключевые слова: кольцевое токосъемное устройство, контактное кольцо, прочность, пластичность, малоцикловая усталость, надежность, вероятность безотказной работы.

Ensuring durability and reliability of contact rings of current collection devices when working in elastic-plastic state

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The reliability of ring current-collecting devices during a given service life plays a decisive role in the operation of power supply systems of various equipment and largely depends on the strength and reliability of all its components, in particular, contact rings. One of the most important characteristics of ring current collectors is the contact resistance, which is reduced by using non-ferrous and precious materials with low resistance, while increasing the downforce between the rings of the current collector. With an increase in the compression force F of the contact ring, the resistance of the contacts decreases to a certain minimum value and practically does not decrease with further growth of the force. The dependence of the contact resistance on the compression force has the form of a power function, the coefficients of which are determined experimentally.

However, the operability of the contact rings in such severe conditions can be ensured in the case of low speeds and a small number of loading cycles by using the low-cycle fatigue area on the Weller curve. Having determined the coefficients of the equation of the inclined section on the Weller curve in the area of low-cycle fatigue, it is possible to determine the number of permissible loading cycles at a given stress level or solve the inverse problem of determining the permissible stress level if the number of loading cycles is known. To substantiate the correctness of the selected compressive force and the corresponding stresses, methods for calculating the fatigue margin coefficient, as well as a method for calculating the reliability of the ring material, are proposed. Reliability is estimated by the Gauss curve and is numerically expressed in the form of the probability of failure-free operation and the probability of failure, for which the corresponding theoretical dependencies are obtained.

According to the proposed methods, calculations of the rings of the current-collection device used in EXPRESS-type spacecraft were performed, which showed the operability of the methods and allowed to ensure the required service life of the contact rings and their reliability. A very simple analytical formulation of the methods allows us to solve both verification and design calculations of rings, depending on the task at hand.

Keywords: ring current collector, contact ring, strength, plasticity, low cycle fatigue, reliability, probability of trouble-free operation.

Introduction

Ring current collectors are used to transfer electrical energy from rotating parts to a stationary base in various technologies, for example, in rotating solar panels, rotating platforms of towers, etc. [1–5]. Ensuring the required reliability of operation of a ring current-collector device during a given service life largely depends on the operating conditions of its elements, in particular, slip rings. The main characteristics of a ring current collector are the electrical parameters of the contact, primarily its resistance. The most effective measures to improve conductivity is to use non-ferrous and precious materials (copper, silver, gold, etc.) as contact ring materials that have good electrical characteristics, as well as increasing the clamping force until a minimum contact resistance is obtained [4–18]. However, such materials are very malleable and have low yield strengths, so this approach leads to a rapid increase in stress in the slip ring, which may exceed the yield strength of its material even with relatively low downforce. The situation is aggravated for critical structures, such as communications spacecraft, which must operate autonomously for a long time in orbit (10–12 years or more).

At the same time, if the required number of loading cycles of slip rings is relatively small, then plastic loading of their material is quite possible due to the use of the low-cycle fatigue region on the Weller curve. For this purpose, this work proposes methods for analytical calculation of the stress-strain state of the ring of a current collector, which make it possible to determine the level of effective stresses and provide the required service life of the rings with a given probability of failure-free operation. The correctness of the proposed approach is ensured by the use of well-known provisions of the theory of fatigue and the theory of reliability when calculating mechanical systems.

1. Research objective

The operation of the design of the ring current collector (Fig. 1) is to transfer electrical energy by compressed slip rings 3 located between the outer 1 and inner 2 rings. Since we are considering a very strong compression of the collector ring, in Fig. 1 they are shown in a deformed state. Insulators 4 serve as separators and ensure uniform arrangement of the collector ring around the circumference.

To ensure electrical contact between the inner and outer current–collection rings in a ring current collector during installation, the slip ring is subjected to compression by a given amount of deformational loading Δ, which in the calculation scheme will be replaced by an equivalent force load in the form of force F (Fig. 2, a).

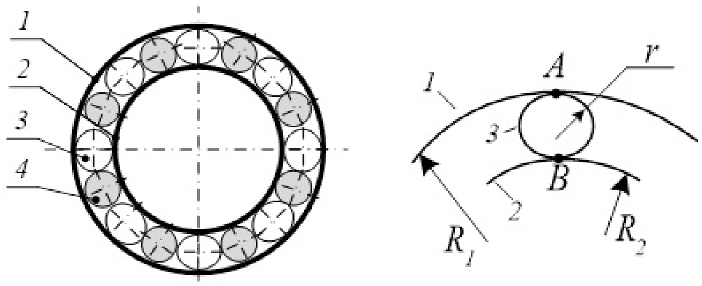
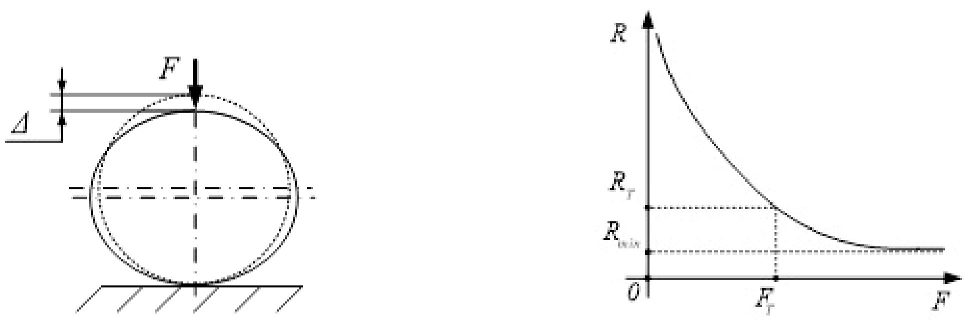


Рис. 1. Конструкция кольцевого токосъемного устройства:
1 – наружное токосъемное кольцо; *2* – внутреннее токосъемное кольцо;
3 – ролик-изолятор; *4* – контактное кольцо

Fig. 1. Design of the ring current collector:
1 – external current–collection ring; *2* – internal current-collection ring;
3 – insulator roller; *4* – contact ring



a *б*

Рис. 2. Нагружение контактного кольца:
а – деформационное и эквивалентное силовое нагружение (сжатие силой *F*);
б – зависимость сопротивления контактов *R* от силы сжатия *F*

Fig. 2. Loading of the contact ring:
a – deformation and equivalent force loading (compression by force F);
b – the dependence of the contact resistance R on the compression force F

With an increase in the compression force *F* of the slip ring, the contact resistance decreases to a certain minimum possible value $R_{\min}$ (Fig. 2, *b*) and practically does not decrease with a further increase in force. The dependence of contact resistance on compression force has a nonlinear form, determined by the empirical formula [8–10]:

$$R_K = k \cdot F^{-m},$$

where m and k – reference constants obtained empirically.

When using pure metals such as copper, silver, gold, etc., the yield strength of the slip ring material can be achieved at a compressive force value R_T at which the contact resistance RT is significantly greater than the minimum achievable value $R_{\min}$. A further increase in the compression force of the slip ring can lead to a violation of the conditions of its strength, therefore it is necessary to develop methods for assessing its performance under plasticity conditions.

We will assume that the rotation speed of the slip rings is so low that we can neglect inertial effects and use the static formulation of the problem for calculations [1]. This is true, for example, for the ring current collector of solar batteries of spacecraft, the rotation speed of which is about 10–4 rpm. The cross-sectional geometry of the slip rings has a rectangular shape (width b and thickness t), the dimensions of which are significantly smaller than the length of their circumference, which allows the theory of rods to be used for calculations [19]. Due to the symmetry of the structure (Fig. 1), the loading conditions of all slip rings are the same, and it is sufficient to consider the stressed state of one ring.

To describe the behavior of the material of a ring made of non-ferrous and precious materials under load, we will accept the model of an ideal elastic-plastic material. In this case, the estimate the state of the material is reduced to checking whether the value of the maximum normal stresses has reached the value of its yield strength.

2. Fatigue task

When the slip ring is compressed, a complex of force factors and corresponding stresses arises in it. Preliminary studies [1] have shown that slip rings operate under conditions of transverse bending due to force F and the determining factor in their stress state is bending normal stresses.

2.1. Maximum bending stresses of slip rings

Normal stress $\sigma_{M_{\max}}$ from bending of slip rings as a result of their compression by force F (Fig. 2, *a*) are determined according to the dependence [19; 20], as

$$\sigma_{M_{\max}} = \frac{M(\varphi)}{W_z} = \frac{Fr}{\pi \cdot W_z}, \tag{1}$$

where $M = Fr\left(\frac{1}{\pi} - \frac{1}{2}\sin\varphi\right)$ – bending moment as a function of the slip ring angle; F – the compressive force equivalent to deformation by an amount Δ is defined as

$$F = \Delta \cdot \frac{2EJS}{r^3 S\left(\pi/4 + 1/4 - 2/\pi\right) + rJ\left(\pi/4 + 1/4\right)}; \tag{2}$$

$J = bt^3/12$ – moment of inertia of the cross section of the ring; $W_z = bt^2/6$ – moment of resistance of the cross section of the ring; Δ – ring deformation; E – Young's modulus; r – average ring radius; S – cross-sectional area of the ring.

The condition for the transition of the slip ring material to the plastic state, according to the adopted calculation scheme, is the condition

$$\sigma_{M_{\max}} \geq \sigma_T. \tag{3}$$

The obtained dependencies (2)–(3) make it possible to determine the compressive strain value of the contact ring at which its material will transition to a state of plasticity. Condition (3) is not a strength condition, since the slip ring is assumed to operate in a plastic state. In this case, it is necessary to ensure fatigue strength, which is discussed below.

2.2. Fatigue strength of slip rings

During the operation of the current collector, each contact ring continuously rolls over the surfaces of the outer and inner rings (Fig. 1), therefore, each point of the ring is exposed to belt stresses (1) that change cyclically in time from zero to the yield strength of the material with the corresponding sign (Fig. 3).

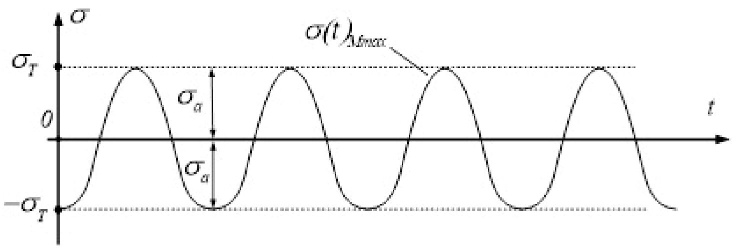


Рис. 3. Симметричный цикл нагружения контактного кольца

Fig. 3. Symmetrical loading cycle of the contact ring

Under cyclic loading, the strength of the material is assessed by the safety factor for fatigue strength based on the Weller fatigue curve [21; 22], which determines the dependence of the material's endurance limit on the number of loading cycles (Fig. 4).

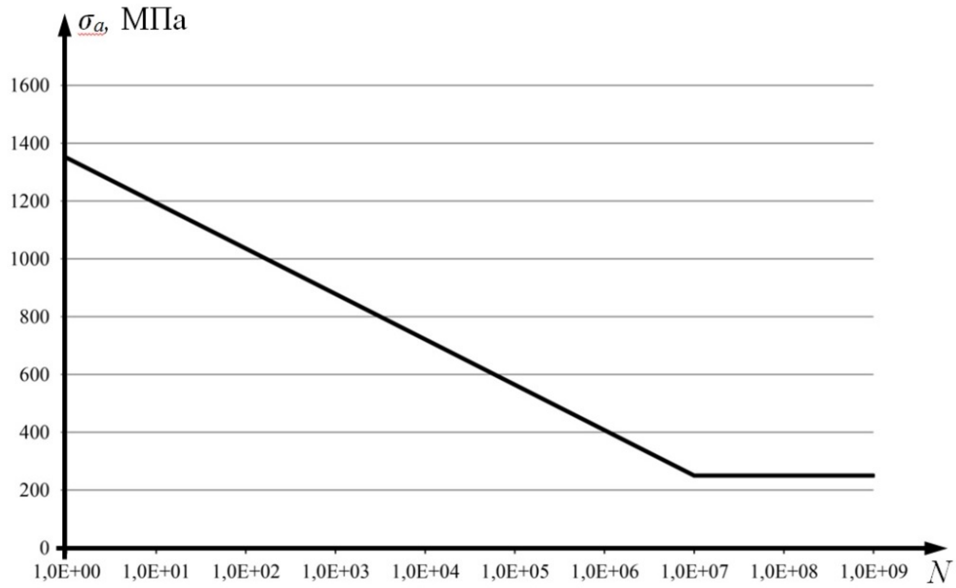


Рис. 4. Пример кривой Веллера в логарифмической шкале

Fig. 4. Example of the Weller curve on a logarithmic scale

According to the Weller curve, it is possible to ensure the ability of the slip ring material to operate under fluid conditions with a number of loading cycles significantly less than the usual fatigue limit (N = 107). This condition is met by low-speed current collectors used, for example, as part of Express-type spacecraft, for which slip rings are subjected to ~$10^4 – 10^5$ load cycles throughout their entire life cycle. These values on the Weller curve correspond to the region of low-cycle fatigue, at which the permissible stresses will be significantly greater than the endurance limit, reaching the yield strength of the material.

The equation for the slope of low-cycle fatigue on a logarithmic scale has the form [23; 24]

$$\sigma_a + K \cdot \lg N = \sigma_{-1}(N) + K \cdot \lg N_0, \tag{4}$$

where σ_{-1} – endurance limit of a material for a given number of loading cycles *N*; σ_a – amplitude of alternating stress and the corresponding number of loading cycles *N* (at $N = 1$ we get $\sigma_a = \sigma_B$); σ_B – tensile strength of slip ring material; *K* – coefficient that determines the angle of inclination of the straight line of fatigue in logarithmic coordinates depending on the physical and mechanical characteristics of the material of the parts being calculated and their dimensions:

$$K = \frac{\sigma_a - \sigma_{-1}}{\lg N_0 - \lg N}.$$

Then you can determine the endurance limit for a given number of loading cycles *N* using the inverse relationship to (4):

$$\sigma_{-1}(N) = \sigma_a + K \cdot (\lg N - K \cdot \lg N_0). \tag{5}$$

The obtained value (5) can be considered the endurance limit for low-cycle fatigue, for which $\sigma_{-1}(N) = \sigma_T$, i.e., the slip ring material will operate under plastic loading conditions.

2.3. Calculation of the fatigue strength of the slip ring

The calculations for the fatigue strength of the slip ring are based on the values of bending stresses at its most dangerous point, at which the bending stresses change according to a cyclic dependence. The minimum and maximum values of bending moments are determined from the dependencies

$$M_{\min}(\varphi) = -Fr\left(\frac{1}{2} - \frac{1}{\pi}\right), \quad M_{\max}(\varphi) = \frac{Fr}{\pi}, \tag{6}$$

to which the stresses correspond

$$\sigma_{\min} = -\frac{F \cdot r}{W_z} \cdot \left(\frac{1}{2} - \frac{1}{\pi}\right), \quad \sigma_{\max} = \frac{F \cdot r}{\pi \cdot W_z}. \tag{7}$$

The average stress per loading cycle will be:

$$\sigma_m = \frac{\sigma_{\max} + \sigma_{\min}}{2}. \tag{8}$$

Amplitude of stress:

$$\sigma_a = \frac{\sigma_{\max} - \sigma_{\min}}{2}. \tag{9}$$

Using the results of calculations using formulas (6)–(9), we obtain a safety factor for fatigue strength for the slip ring equal to:

$$n = \frac{\sigma_{-1}}{\sigma_a \dfrac{K_\sigma}{K_d \beta_\sigma} + \psi_\sigma \sigma_m}, \tag{10}$$

where σ_{-1} – endurance limit; K_σ – effective stress concentration factor,

$$K_\sigma = \frac{\sigma_{\max.\text{эфф}}}{\sigma_H} = 1 + q_\sigma(\alpha_\sigma - 1),$$

where q_σ – material sensitivity coefficient to stress concentrations; α_σ – stress concentration factor:

$$\alpha_\sigma = \frac{\sigma_{\max}}{\sigma_H};$$

K_d – coefficient of influence of absolute cross-sectional dimensions:

$$K_d = \frac{(\sigma_{-1})_d}{\sigma_{-1}},$$

where $(\sigma_{-1})_d$ – endurance limit of smooth samples with diameter d; σ_{-1} – endurance limit for standard samples;
β_σ – part surface condition coefficient:

$$\beta_\sigma = \frac{(\sigma_{-1K})_Д}{(\sigma_{-1K})_d},$$

where $(\sigma_{-1K})_Д$ – endurance limit of a full-scale part;
ψ_σ – cycle asymmetry sensitivity factor.

The actual service life of the slip ring, based on the known values яf the amplitudes of alternating stresses and the theoretical value of the safety factor for fatigue strength, can theoretically be determined from the dependence

$$N_{факт} = 10^{\frac{\sigma_{-1}(N)}{K} + \lg N_0 - \sigma_a N}, \quad (11)$$

where $\sigma_{-1}(N)$ – endurance limit for low-cycle fatigue, determined by the formula (5).

2.4. Reliability of slip rings

The reliability of slip rings in a plastic state is determined by the probability of its failure-free operation [25–28]. The condition for destruction is that the maximum stress in the slip ring exceeds the endurance limit of the material of this ring:

$$\sigma_{max} = \sigma_{M_{max}} > \sigma_{-1}(N).$$

Let us introduce the non-destruction function in the form of the difference

$$\Delta\sigma = \sigma_{-1}(N) - \sigma_{max}.$$

We are considering σ_{max} и $\sigma_{-1}(N)$ as random variables and we assume that their values have a normal distribution, for which the statistical parameters are known:

1) average values

$$\bar{\sigma}_{max} \text{ and } \bar{\sigma}_{-1};$$

2) standard deviation

$$S_{\Delta\sigma} = \sqrt{S^2_{\sigma_{-1}} + S^2_{\sigma_{max}}}.$$

Then the probability of destruction corresponds to the probability of fulfilling the condition

$$P_{fail} = P(\Delta\sigma) = P \quad (\text{at } \Delta\sigma < 0) = F(0),$$

and the probability of failure-free operation is equal to

$$P_{free} = 1 - P_{fail}. \quad (12)$$

Here the function $P(\Delta\sigma)$ is distribution function of a random variable $\Delta\sigma$:

$$P(\Delta\sigma) = \frac{1}{2} + \Phi\left(\frac{\Delta\sigma - \overline{\Delta\sigma}}{S_{\Delta\sigma}}\right),$$

where $\Phi(x)$ – Laplace function:

$$\Phi(x) = \frac{1}{\sqrt{2\pi}} \int_0^x e^{\left(-\frac{u^2}{2}\right)} du.$$

Let's denote

$$\upsilon_{\Delta\sigma} = \frac{S_{\Delta\sigma}}{\overline{\Delta\sigma}} = \frac{\sqrt{S_{\sigma_{-1}}^2 + S_{\sigma_{\max}}^2}}{\overline{\sigma}_{-1} - \overline{\sigma}_{\max}}.$$

Using an approximate representation of the Laplace function [25], the expression for the probability of destruction will take the form of a power series:

$$P_{\text{разр}} = \frac{\upsilon_{\Delta\sigma}}{\sqrt{2\pi}} \cdot e^{\left(-\frac{1}{2\upsilon_{\Delta\sigma}^2}\right)} \cdot \left(1 - \upsilon_{\Delta\sigma}^2 + 3\upsilon_{\Delta\sigma}^4 - \upsilon_{\Delta\sigma}^6 + \ldots\right). \quad (13)$$

After substituting the values into expression (12) and limiting ourselves to the terms of the series up to the 6th degree inclusive, we obtain the values of the probability of destruction (13) and failure-free operation (12) of the slip ring.

3. Slip ring calculation example

Using the obtained dependencies, we will perform calculations of the durability and probability of failure-free operation for the slip rings of the current-collector device of the Express-type spacecraft. To do this, we accept the following initial data: R_1 = 30 mm, R_2 = 25 mm, r = 9.9 mm, S = 0.36 mm^2, Δ = 0.4 mm. Material: bronze alloy BrB2, σ_{-1} = 591 MPa.

Calculation of force factors using dependencies (2)–(4) gives the values W = 6.25 · 10^{-9} m^3, J = 1.56 · 10^{-11} m^4, F = 5 H, $M_{\max}$ = 0.008 N · m. sing these values, we obtain the results of calculating the slip ring for fatigue strength, presented in Table 1.

Table 1

Calculation results for the fatigue strength of the slip ring

Ring tension Δ, mm	$\sigma_{\min}$, MPa	$\sigma_{\max}$, MPa	σ_m, MPa	σ_a, MPa	σ_{-1}, MPa	K_σ	K_d	β_σ	ψ_σ	n
0.4	–303	532	114.4	418	591	1.22	1	1.1	0.1	1.24

The results of calculating the probability of destruction and failure-free operation of the slip ring are given in Table 2.

Table 2

Results of calculating the probability of failure-free operation of the slip ring

Ring tension Δ, mm	Eq. Force F, H	σ_{-1}, MPa	$\sigma_{\max}$, MPa	$\Delta\sigma$, MPa	$\overline{\sigma}_{\max}$, MPa	$\overline{\sigma}_{-1}$, MPa	$S_{\Delta\sigma}$	$\upsilon_{\Delta\sigma}$	$P_{\text{разр}}$	P_{free}
0.4	5	591	418	62	418	591	48	0.229	6.77 · 10^{-6}	0.999 99

The obtained values of the safety factor for fatigue strength n = 1.24 and probability of failure-free operation P_{free} = 0.999 99 meet the requirements for the design of current collectors for Express-type spacecraft.

4. Discussion of the results

The methods proposed in the work for calculating slip rings for fatigue and the probability of failure-free operation are based on the assumptions of the classical theory of rods, which introduces some error into the calculations. For example, in calculations the radius of the ring r remains constant, although upon compression the ring transforms into an ellipse, in which one focal radius will be slightly less than the original radius value. This will lead to a slight increase in the actual values of bending stresses. Additionally, the growth of stresses would be facilitated by taking into account stresses from transverse and longitudinal forces, for a comprehensive assessment of which it would be necessary to use one of the strength theories. However, the calculations showed that taking these factors into account will lead to a change in the results by only 2–3 %, which allows us to remain within the framework of the classical theory and simple analytical dependencies.

The experiments showed that a more significant increase in the fatigue limit of the material occurs with a decrease in the size of the slip ring, its surface roughness and rounding of the edges to reduce the possible stress concentration near geometric inhomogeneities. An analytical description of these dependencies and methods for taking them into account in engineering calculations have not yet been fully obtained. Their influence can be assessed only indirectly, for example, by the ratio of the sizes of standard samples and the parts under study (rings). Standard fatigue samples have a circular cross-section with a diameter of about 7–10 mm. The thickness of the slip rings is only 0.25 mm, which is an order of magnitude smaller than the standard value and implies a significant increase in the actual service life of the slip ring (11) compared to the theoretically calculated value.

Temperature also affects the endurance of the slip ring [28]. Analyzing the results of studies on the effect of temperature on the endurance limit of bronze alloys, it was found that when the temperature decreases, the values of the endurance limit increase slightly, and when it increases, it first gradually and then decreases more and more rapidly. Moreover, up to a temperature of +100° these changes can be neglected in practical calculations due to the insignificance of their effect.

The possibility of thermal fatigue of the slip ring material was not considered, since under low-cycle loading it begins to manifest itself at temperatures from 30°C in the presence of zones of large temperature gradients and sharp changes in stress. In the case of thin-walled slip rings, according to the initial data received from JSC RESHETNYOV, temperature differences of less than 20° occur, which will not affect either the structure of the ring material or its mechanical properties. The rate of change in the temperature of the rings from –30° to +80° per day is very small, which leads to an almost uniform temperature field of the current collector.

The coefficients of thermal expansion of the materials of the contact outer and inner rings, according to available reference data, are identical over a wide temperature range. This leads to the same relative deformation of all rings that make up the current collection unit. The conditions for fastening and operating the slip rings are such that heating begins from the outer ring and the temperature values drop near the inner ring. Consequently, the resulting gradients will lead to a greater expansion of the outer ring compared to the inner one, which will lead to a decrease in interference and, thus, a decrease in the amplitude values of alternating stresses. The absolute values of the thermal deformation of the rings depend on the value of the thermal expansion coefficients of their material and are approximately 1000 times smaller than the interference values, therefore the effect of temperature stresses on the strength and fatigue of slip rings can be neglected.

Conclusion

The paper proposes methods for analytical calculation of the stress-strain state of slip rings during the operation of ring current-collecting devices of spacecraft. The methods are based on the well-known principles of fatigue theory and reliability theory, which make it possible to ensure the required fatigue strength and reliability of slip rings operating under plasticity conditions for a given service life or number of loading cycles.

The technique can be used to justify the adoption of design and technological decisions when designing new or testing existing ring current collectors. The simple formulation of the methods makes it possible to solve both verification and design calculations of rings depending on the task at hand and analytically determine almost any design parameter.

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