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STRESS-STRAIN STATE AND WEAR MODELLING FOR FUEL ROD – GRID CONTACT

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The paper presents an approach for effective solution of the stress-strain state and wear prediction problem for the case of contact between fuel rod and grid surfaces of a nuclear reactor. Boundary-initial value elastic-plastic problem statement, due to the quasi-static character of the forced oscillations, which was approved by eigen frequencies analysis, was reduced to boundary one. The influence of inhomogeneous temperature field and varying pressure in the outer surface of fuel rod’s shell are considered. For this, a sequence of special procedures for searching the most effective ways of numerical simulation with limited computational resources was considered. The method of weighted residuals and the finite difference method were used to solve the problem of nonlinear forced oscillations under periodic loading of the fuel rod, described as beam under bending. The analytical solution for the fuel rod’s shell displacements in thermo-elasticity problem is obtained, approximated for spatial case and added to the general three-dimensional Finite Element model. The same procedure was adopted for the maximum amplitude values of the displacements which were obtained in the geometrically nonlinear beam problem solution. After that the general elastic-plastic contact problem of the interaction between the fuel rod and the grid surfaces was solved, taking into account preliminary obtained stress distributions achieved by temperature and amplitude displacements influence. The theory of plasticity of an isotropic material with isotropic hardening was used as a model. The limits of linear solutions for beam deflections as well as deflection dependencies upon time are demonstrated and analyzed. The numerically obtained distributions of strains and stresses are presented. By use of the obtained maximum stress values an attempt for the wear estimation in contact zone was done and the fuel rod’s operating time without critical wear during the contact with the grid surface was determined. The obtained results may be considered as corresponding to practical operating data.

INTRODUCTION

The problems of the long-term strength of engineering components are of great importance. In the case of nuclear reactor vessel internals (RVI) the solution of such problems in a design stage is extremely necessary due to the security demands.

One of the dangerous processes which take place in reactor is wear of the fuel rods at time of their contact with support surfaces [1]. With the long-term contact of surfaces in a large number of cases, their wear occurs, which means a change in the shape of one or both surfaces. Such processes are studied by a special branch of mechanics – tribology [1, 2]. Tribology is the science of describing interacting surfaces. The nature and consequences of the interactions, that occur at the interface, control surface friction. During these interactions, forces are transferred, mechanical energy is transformed, and the physical and chemical nature, including the topography of the interacting materials’ surfaces, are changed. Understanding the nature of these interactions and solving the technological problems associated with interfacial phenomena are essential for tribology. Friction is the resistance to motion that is experienced when one solid body moves over another [1]. Wear is surface damage or removal of material from one or both of two solid surfaces in moving contact [1]. Special materials, coatings and surface treatments are used to control friction and wear. To achieve optimal performance and reliability, the role of surface stiffness, coupling mechanisms, friction and wear must be understood. The importance of friction and wear control cannot be overstated for economic reasons and long-term reliability.

The theoretical foundations of the description of friction and wear processes are provided in [1, 2]. Since the purpose of the paper is to evaluate the interaction between the surfaces of fuel rods and grid support surfaces, we will highlight these main components of considered papers and books. The main approaches to the description of contacting surfaces and directly the processes of contact interaction are presented in [1]. The main models of friction are described. The main constitutive equations which are used for the description of wear of different natures – abrasive, adhesive, fatigue, impact and others – are presented.

A description of models and methods of computational hydrodynamics, which are necessary for friction calculations, contains in [2]. The main approaches to the description of the contact between solids are considered. Abrasive wear models for various structural materials are described, methods of taking into account the influence of temperatures and liquids are provided. Considerable attention is paid to corrosion wear, transitions between it and other types of surface degradation.

Investigations in the direction of evaluating the complex nonlinear behavior of structural elements during the interaction of dynamic, contact, and tribological processes, including the RVI analysis, continues to be relevant. The results of modeling the flow field and vibrational response of fuel rods in the reactor core are presented in [3]. The influence of assembly bending on the flow field in the active zone of the reactor is discussed. In order to provide an evaluation of the flow field varying on fuel vibration and wear characteristics, the flow field calculations were linked to the flow induced vibration analysis code. The WEstinghouse Computer ANalysis (WECAN) structural analysis code was used to determine the rod natural frequencies and mode shapes for various reference conditions, which are used as input to the vibration analysis code. This combined approach makes it possible to determine average wear rates. A combined analysis of the flow field and fuel rod vibration response was compared with assembly wear data. The results of the control test on the mid-range amplitude and wear volume are presented and discussed, which was considered as an initial step towards the development of a predictive model for the reactor core.

It is emphasized in [4] that the wear of fuel rods is caused by a complex combination of factors. Fuel rod excitation and motion relative to its supports can be caused by the coolant flow and mechanical forces. The response amplitude for a given set of flows and mechanical forces depends on the fuel rod and its support system. The mass of the fuel, stiffness and location of supports along its length dictate the mode shapes and natural frequencies. The contact geometry between the support system and the fuel rod is also an important factor. The types of flow conditions that can exist in the reactor core and how they will lead to excitation of the fuel rod, and how the relative motion of the rod to its supports can lead to wear, are considered. Test methods are discussed, ranging from microscopic and single-cell tests to high-temperature and full-scale fuel assembly tests at high temperatures and flows.

In is also notes in [5] that during the examination of the main cause of fuel failure in a pressurized water reactor (PWR) in 2004, it was found that the fuel assemblies located on the core partition have various signs of fuel rod wear.

In this complex analysis, an adequate description of the dynamics of fuel rods is important. Dynamic models of the fuel assembly were developed in [6] for seismic analysis of the active zone of the reactor. The fuel assembly is modeled by one vertical beam, taking into account the inertia of the cross-section of fuel rods, tips, and a number of springs. Comparison the natural frequencies of the fuel assembly, determined by the test, is carried out by adjusting the inertia moment and rotational stiffness of the grid to find their effective values. Most often, these models are linear and suitable for determining small amplitudes. It is noted that in practice, large deflections are approximated by choosing a fuel stiffness value that corresponds to the average deflection range. This approach naturally leads to a certain loss of accuracy. The paper [6] presents a nonlinear model for the approximation of hysteresis and free vibration response for large amplitudes of the fuel assembly motion. It is noted to correctly predict fuel assembly deflection shapes as a function of axial position for various lateral loads for several fuel assembly designs, provide a better fit to the grid shock load task, and better fit all initial conditions (initial deflection, initial force, initial energy and impact velocity).

This paper contains an attempt to present the first version of the approach and calculation method for determining the stress-strain state and wear prediction of the fuel rod and grid surface contact.

PROBLEM STATEMENT

General mathematical problem statement of the considered task presents by the system of differential equations for the solid which material deforms at elastic-plastic mode. Let us consider the mathematical formulation for the solid Ω, which has boundary surface $\mathit{\Gamma}$. Let us apply the Cartesian coordinate system $\mathbf{x}(x_i), i=1,2,3$. We assume that in a part of the volume surface $\mathit{\Gamma}_1$ the values of displacements are given: $u_i\big|_{\Gamma_1}=\tilde{u}_i$. Part of the surface $\mathit{\Gamma}_2$ is loaded by traction $\tau_i(x_i,t)$, and static volume forces are considered absent. We assume that the elastic and plastic properties of the material are isotropic. The inhomogeneous temperature field $T(x_i)$ is acted through the solid's volume.

We apply the Lagrangian approach and consider the case of small strains at general statement. We accept the following notations: $\mathbf{u}=\mathbf{u}(x_i,t)$ is the displacement vector; $\boldsymbol{\varepsilon}=\boldsymbol{\varepsilon}(x_i,t)$ is the strain tensor; $\boldsymbol{\sigma}=\boldsymbol{\sigma}(x_i,t)$ is the stress tensor, t is the time variable. We use the hypothesis of strains additivity

$$\varepsilon_{ij}=\varepsilon_{ij}^{e}+\varepsilon_{ij}^{T}+p_{ij}+c_{ij}, \tag{1}$$

where total strain component ε_{ij} consists of elastic ε_{ij}^{e}, temperature ε_{ij}^{T}, plastic p_{ij} and creep c_{ij} components. The last one will not be considered in this paper because of necessity the main assumptions verifying. The approach for their further consideration can be found at [7, 8]:

$$\begin{gathered}
\sigma_{ij,j}=\rho\ddot{u}_i;\ \sigma_{ij}n_j=\tau_i(\mathbf{x});\ \mathbf{x}\in\Gamma_2;\\
\varepsilon_{ij}=\frac{1}{2}\left(u_{i,j}+u_{j,i}\right),\ \mathbf{x}\in\Omega;\ u_i\big|_{\Gamma_1}=\tilde{u}_i;\ \mathbf{x}\in\Gamma_1;\\
\sigma_{ij}=C_{ijkl}\left(\varepsilon_{ij}-\varepsilon_{ij}^{T}-p_{ij}-c_{ij}\right);\\
\bar{f}\left(\sigma_{ij}\right)=\frac{3}{2}s_{ij}s_{ij}-\left[\Phi\left(\int d\bar{p}_i\right)\right]^2; \qquad (2)\\
p_i=\Phi\left(\int d\bar{p}_i\right);\ dp_{ij}=\frac{3}{2}\ \frac{d\bar{p}_i}{\sigma_i}s_{ij}.\ i,j=1,2,3.
\end{gathered}$$

Here $n(n_i)$ denotes the unit vector normal to the volume's surface; ρ is the density of material.

To determine the plastic strains, we apply the theory of isotropic hardening plasticity [9]. The Huber-Mises plasticity condition is used. Here s_{ij} are deviatoric components of the stress tensor, $\int d\bar{p}_i$ is the Odquist parameter, and p_i is the von Mises equivalent strain.

The character of traction $\tau_i(x_i,t)$ in considered problem of interaction between fuel rod and grid surfaces cannot be determined directly. It is determined by the contact pressure which is varied due to the oscillations of the fuel rod, caused by pulsations of temperature or gas in gas cooled reactors. The character of this pressure varying is complex and can be determined directly by the solution of complete Fluid Mechanics problem.

In this paper only first attempt to obtain the numerical values of a pressure is presented. Let us suppose, that the fuel rod due to the simplified character of an external pressure makes bending forced oscillations in one plane, but its finite deflections are considered.

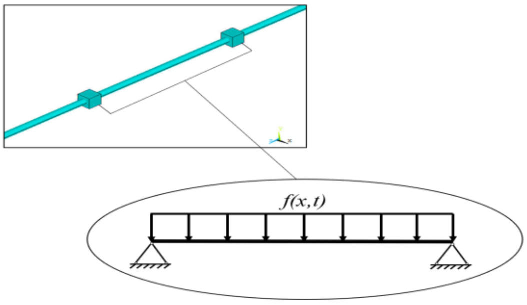


Fig. 1. Computational scheme for modelling the fuel rod's forced oscillations

Further let us describe the oscillations of the fuel rod's domain between two supports in plate by use of a beam theory, which can be done in considered case due to the known ratio between length and cross-sectional dimensions of a rod (Fig. 1). A hinged supported beam is used as a mechanical model at the first stage, the material of which is considered to be isotropic, the cross section is not deformed in its plane. A periodic load $f(x,t)$ acts on the beam, which simulates the flow influence. Oscillations are generally described by the following nonlinear equation with given boundary and initial conditions [10]:

$$\frac{\partial^2 u(x,t)}{\partial t^2} + a^2\frac{\partial^4 u(x,t)}{\partial x^4} + $$
$$+C\frac{\partial^2 u(x,t)}{\partial x^2}\int_0^l\left(\frac{\partial^2 u(x,t)}{\partial x^2}\right)^2 dx = f(x,t). \qquad (3)$$

Here $u(x,t)$ is a beam's deflection. It is the function of two variables: x (rod's length variable) and time t; $a^2 = EI/\rho S$ is a coefficient that depends on the parameters of the rod; $C = E/2l\rho$ is the coefficient for the geometrically nonlinear part of the equation; E is the Young modulus; I is the 2nd order moment of area; S is the cross-sectional area; l is the beam's length.

In general case the function $f(x,t)$ consists of two terms:

$$f(x,t) = f_0 + f_a\cos(2\pi\omega), \qquad (4)$$

where f_0 corresponds to constant, static part of loading as well as second term describes it's varying part by the amplitude value f_a and frequency ω. In first approximation we use harmonic law.

Boundary conditions for the case of hinged beam are given in the form

$$u(0,t) = \frac{\partial^2 u(0,t)}{\partial x^2} = u(l,t) = \frac{\partial^2 u(l,t)}{\partial x^2} = 0. \qquad (5)$$

The homogeneous initial conditions are used:

$$u(x,0) = u_0(x);\ \dot{u}(x,0) = 0. \qquad (6)$$

The aim of this equation solution is obtaining the function $u(x,t)$. Further it will be used in general 3D problem statement as displacement distribution under the contact between the fuel rod and grid support surfaces.

USING GALERKIN METHOD FOR MODELLING FORCED OSCILLATIONS

The method of weighted residuals in Galerkin form [11] will be used here in order to solve the equation (3) with additional conditions (5) and (6).

First of all, let us limit by the quasi-static problem solution without considering the inertia forces. This limitation is possible due to the preliminary obtained values of the beam's eigen frequencies. The values of considered beam eigen frequencies have the following form:

$$p_i = \frac{i^2\pi^2}{l^2}\sqrt{\frac{EI}{\rho S}}\ (i = 1,2,3,...). \qquad (7)$$

The first one $p_1 = 72.46$ Hz, which is much greater the known values of forced oscillations frequencies of fuel rods with values 1...2 Hz [7]. So, we can suppose, that fuel rod's motion can be considered as quasi-static. The following equation is solved:

$$a^2\frac{\partial^4 u(x,t)}{\partial x^4} = f(x,t) -$$
$$-C\frac{\partial^2 u(x,t)}{\partial x^2}\int_0^l\left(\frac{\partial^2 u(x,t)}{\partial x^2}\right)^2 dx. \qquad (8)$$

Let us briefly present the main steps of well-known Galerkin approach which are necessary in order to solve the above stated beam force oscillations problem. At first step it is necessary to determine the initial deflection by solving the equation (8) at $t = 0$, when only action of f_0 presents. The deflection $u(x)$ is found by use of the approximation with selected sine basic functions:

$$u(x) \approx \hat{u}(x) = \sum_{i=1}^{M} a_i \sin\frac{\pi(2i-1)}{l}x. \qquad (9)$$

The equation of weighted residuals takes the following form:

$$\int_0^l \sin\frac{\pi(2k-1)}{l}x\left(\frac{d^4\hat{u}}{dx^4} - f_0\right)dx = 0,\ k = 1...M. \qquad (10)$$

It coincides with the system of algebraic equations of dimension *M*. After it's solving the expansion coefficients are obtained, which leads to determining the function (9).

In the next step we put the obtained solution in the form (9) into the (8):

$$a^2\frac{\partial^4 \hat{u}(x,t)}{\partial x^4} = f(x,t) -$$

$$-C\frac{\partial^2\hat{u}(x,t)}{\partial x^2}\int_0^l\left(\frac{\partial^2\hat{u}(x,t)}{\partial x^2}\right)dx \tag{11}$$

after which we solve it using the same method of weighted residuals. The procedure with using finite differences method is repeated until the convergence of the results over time is established. The proposed algorithm is realized using MATLAB.

Let us consider a beam with length $l = 0.2355$ m, which is a model of a section of fuel rod between two contacting grid surfaces, with a radius $r = 0.00455$ m (cross section $S = 6.5\cdot10^{-5}\,\mathrm{m}^2$) (see Fig. 1). Given that the cladding material is zirconium, the following values of physical and mechanical constants were used: density $\rho = 6550\ \mathrm{kg/m}^3$, Young modulus $E = 76.2\cdot10^3$ MPa, Poisson's ratio 0.33. In the first approximation, we use the following parameters of the external loading: $f_0 = 120\ N/\mathrm{m}^2$, $f_a = 30\ N/\mathrm{m}^2$, $\omega = 2$ Hz.

The obtained results are shown in Figs. 2, 3. The curve 2 in Fig. 2 shows the dependence of the maximum deviation on the acting force for the linear case, and the curve 1 shows the nonlinear case. So, we can see substantial difference between them starting from the values are equal to $60...70\ N/m^2$.

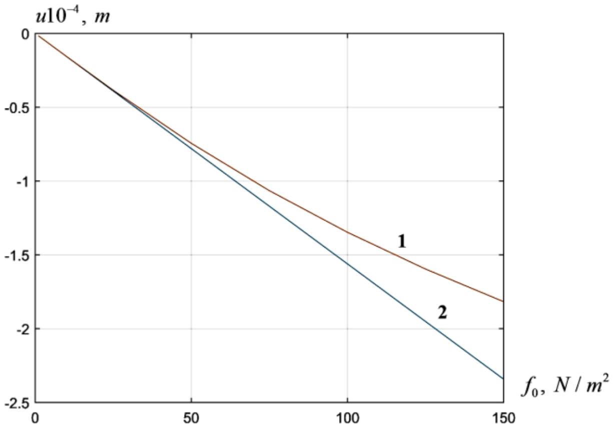


Fig. 2. Beam deflection versus load

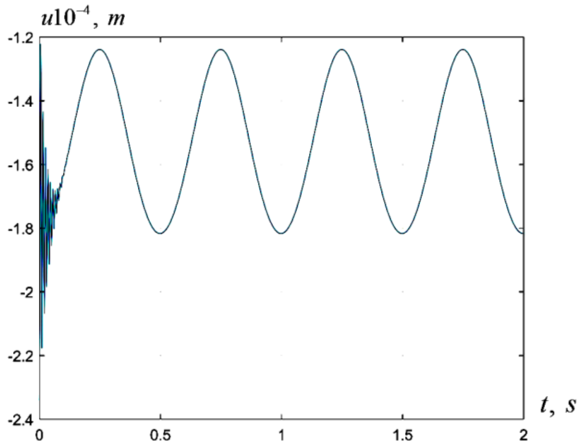


Fig. 3. Beam deflection versus time

Next, consider the geometrically nonlinear oscillations of the beam. The results are shown on Fig. 3 for the middle point of the beam, when the maximum values of the deflection take place.

Analysis of Fig. 3 shows, that the beam's deflections were fast passed to the forced oscillations mode and their steady state maximum value can be determined. This value will be used in the following 3D modeling of stress-strain state in contact zone between fuel rod and grid surfaces as initial distribution which caused additional stresses.

FINITE ELEMENT ANALYSIS (FEA) OF FUEL ROD STRESS-STRAIN STATE

The complex 3D problem presented by system (2) is solved by Finite Element Method (FEM) [11]. Let us consider the fragment of the fuel rod between two grids and the part of one of them with a hole, where the contact of surfaces takes place (Fig. 4). The fuel rod consists of nuclear fuel material, which is considered as an inner cylinder, and an outer fuel rod's cladding. The material of the cladding and grid plates is zirconium doped with 1% niobium, its yield strength in analyzed temperature range is following: $\sigma_y = 310$ MPa.

The geometric parameters of the fuel rod fragment have the following characteristics: the diameter of the fuel cladding is 9.1 mm, its length between the grids is 0.2355 m, the thickness of the grid plate is 17.5 mm, the diameter of the its hole is equal to 9.6 mm.

To solve the problem, we build a finite element model of a fuel rod fragment with its contact with grid element. Due to the fact that the problem is symmetric with respect to the grids, the part of the fragment shown in Fig. 4 is considered. The symmetry conditions at the fuel rod's edges are introduced. The hinged fastening of the fuel rod in the place of contact with the grid surface is achieved.

Let's consider the problem in a quasi-static statement and set the deflection of the fuel rod's fragment at the maximum possible amplitude of oscillations. We take into account the presence of contact interaction between the hole in the grid plate and the outer surface of the fuel rod shell.

For the purposes of convergence validation, numerical studies were done for the different finite element models with number of elements from 135323 to 499899, one of them is presented on Fig. 4. Note that a condensed mesh is applied in the contact region and nearby regions.

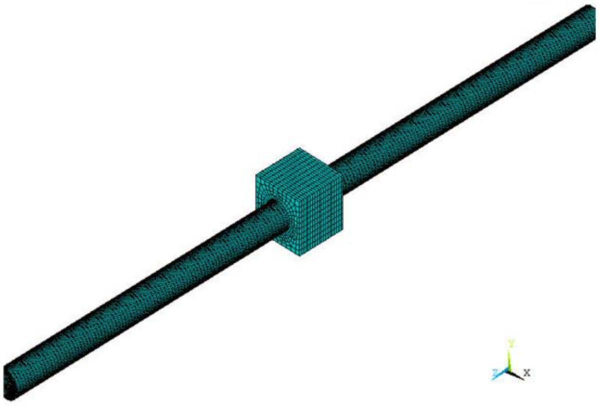


Fig. 4. Finite element model for fragments of fuel rod and grid

Let us pay attention to the solution of thermoelastic part of the problem. The typical stationary temperature radial distribution across the rod's shell thickness with difference 20 °C from inner to outer surface was considered. From the FEA experience it is well known [11], that the adequate value of thermal stresses through cylinder thickness can be obtained by use of a FE net with a sufficient number of elements. Due to the small thickness of a cladding this issue leads to extremely large dimension of a problem. Besides, the direct simulation at edges will lead to non-existent stresses with high values.

That is why another method for considering thermal stresses in total calculation scheme was adopted. Its use is possible in this case due to the existing of analytical solution for thermoelastic problem of long thick tube [9]. As it is known, in this case temperature distribution follows the logarithmic law:

$$T(r)=\frac{T_{inner}\ln(\dfrac{r}{R_{outer}})-T_{outer}\ln(\dfrac{r}{R_{inner}})}{\ln(\dfrac{R_{inner}}{R_{outer}})}\ . \qquad (12)$$

The function of shell displacements upon radius, which was obtained by use of analytical solution, was approximated for 3D case and specified for calculation scheme (Fig. 5).

So, the final calculational scheme, which used in FEA, includes two displacement distributions, which were preliminary determined by use of nonlinear oscillations modelling as well as obtained by use of analytical determined displacements from thermoelastic problem. These displacement distributions were used for the analysis of additional stresses. Due to the fact, that preliminary elastic modelling showed the stress values which considerably exceeded the yield strength of the material, the elastic-plastic formulation of the problem with contact consideration was used. The obtained results in the form of von Mises strain ε_{vM} (Fig. 6) and stress σ_{vM}, Pa distributions (Fig. 7) are presented below.

Obtained stress distributions allow us to start the wear analysis in the contact area.

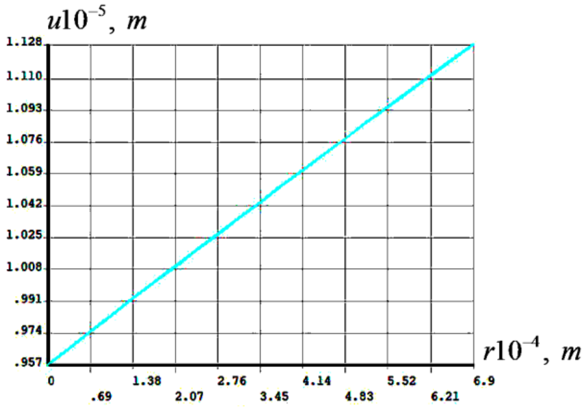


Fig. 5. Radial thermal displacements versus shell radius

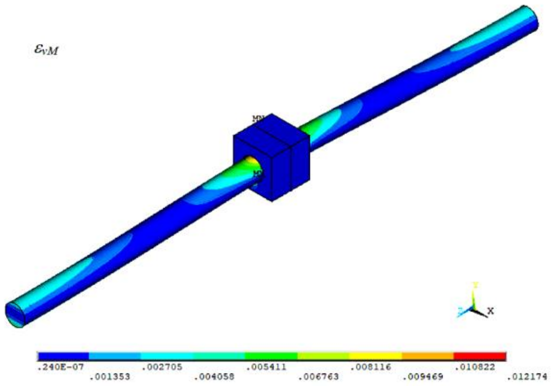
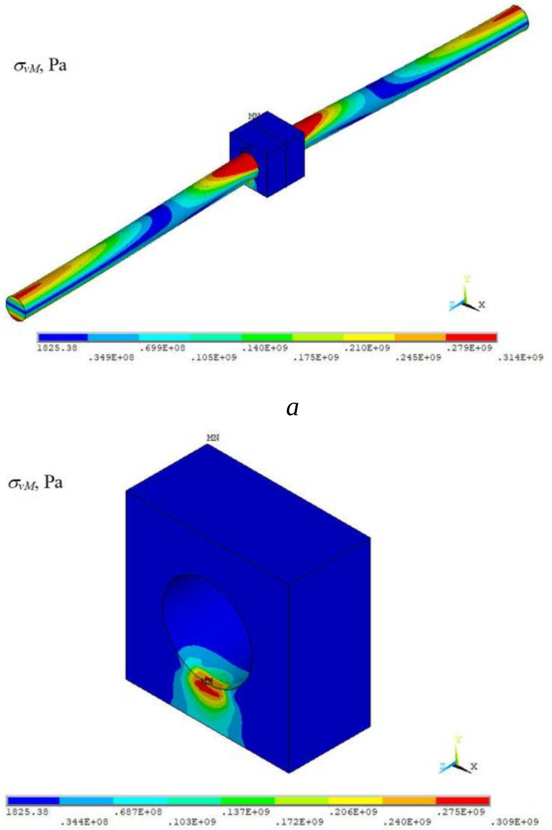


Fig. 6. Distribution of von Mises equivalent strain over the surface of the model



b

Fig. 7. Distribution of von Mises equivalent stress, Pa over the surface of the model (a) and at place of contact (b)

WEAR MODELLING IN CONTACT AREA

It is known [1], that adhesive and abrasive wear mechanisms operate during direct physical contact of two surfaces moving relative to each other. If the contact stresses are relatively high, a fatigue mechanism may take place.

From Hertz's analysis of elastic ratios, the maximum compressive stresses occur at the surface. The time to fatigue failure depends on the stress amplitude and fatigue properties of the materials [1].

According to the AFBMA approach [1], the operating time of the structural element during wear t_w can be estimated in the first approximation as

$$t_w = \left(\frac{C}{W}\right)^p \cdot 10^6 / (rpm \cdot 60), \qquad (13)$$

where C is the maximum radial load; W – realized load; p is a constant determined experimentally. For the case of point (hereinafter surface) contact, its value is equal to 3; rpm – the number of revolutions per minute.

Let us apply this approach to determine the operating time of the fuel rod without critical wear when it is in contact with the grid surface. Let's define the load values included in the ratio (13). As the maximum C, we will take the one that corresponds to the value of the fracture stress (the ultimate strength limit) $\sigma_u = 660$ MPa, for the case under consideration. To determine the value of the force, it is necessary to know the area on which the corresponding stress acts. Let's take as an example the value of the contact area S_c of the fuel rod with the grid surface, in which the strains reach 0.9%.

Next, it is possible to determine the resultant force acting on this area. It is approximately equal to the product of the equivalent stress by the size of the area. We choose the maximum value of the realized stress, which is 314 MPa, then $W = S_c \cdot 330$ MPa. To calculate the value of the maximum radial load *C*, we will choose the value of the ultimate strength of the fuel shell material at a given temperature, $C = S_c \cdot 660$ MPa. As can be seen from the analysis of Eq. (13) during calculations, the area values S_c in the numerator and denominator are mutually reduced.

Next, assuming a fuel oscillation frequency of $\omega = 1$ Hz, we get a value of $rpm = 60$. Finally, we get the operating time of the structural element during wear $t_w = 2572$ h. In the case of $\omega = 2$ Hz, this value is decreased twice and we have $t_w = 1286$ h.

This means that under the conditions of the specified loads, the operating time of the fuel rod is 0.125…0.25 years. This corresponds to operational data, according to which this time does not exceed six months. Therefore, the calculations provide a lower estimate of the wear time, which can be considered satisfactory from the point of view of the possibility of incomplete consideration of various operational factors.

CONCLUSIONS

An approach and sequence of procedures for effective solution of the stress-strain state problem for the case of contact between fuel rod and grid surfaces of a nuclear reactor are presented in a paper. The results of numerical simulation are used in the procedure of simplified estimation the wear in this area.

The problem was solved as a boundary-initial value elastic-plastic problem. The influence of inhomogeneous temperature field and varying pressure in outer surface of fuel rod's shell are considered. For this, a sequence of special procedures for searching the most effective ways of numerical simulation was proposed.

The eigen oscillations frequencies of the considered fuel rod were determined. The essential difference between frequencies of the first eigen mode and forced oscillations allows us to state the problem as quasi-static. The method of weighted residuals and the finite difference method were used to solve with MATLAB the problem of forced oscillations under periodic loading. The influence of the geometrically nonlinear part of the equation on the obtained solution was studied.

The analytical solution for the fuel rod shell displacements in thermo-elasticity problem was approximated and added to the general 3D FEA. The same procedure was adopted for the maximum amplitude values of the displacements were obtained in geometrically nonlinear beam problem statement. After that the 3D elastic-plastic contact problem of the interaction between the fuel rod and the grid surfaces was solved, taking into account preliminary obtained stress distributions achieved by temperature and amplitude displacements. The theory of plasticity of an isotropic material with isotropic hardening was used as a model.

The obtained distributions of strain-stress state components were analyzed. By use of the obtained maximum stress values an attempt for the wear estimation in the contact zone was done and the fuel rod's operating time without critical wear during the contact with the grid was determined. The obtained results may be considered as corresponding to the practical operating data.

The presented paper contains only first approximation of the problem in consideration. The motion of the fuel rod in real practice can be regarded as 3D, so in this case the contact area can be distributed with more complex shape. The wear analysis can be considered in more complex way, for example by analyzing the surface varying.

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REFERENCES

1. B. Bhushan. *Introduction to tribology* (2nd ed.). John Wiley & Sons, 2013, 711 p.
2. G.W. Stachowiak, A.W. Batchelor. *Engineering Tribology* (3rd ed.). Elsevier Butterworth-Heynemann, 2005, 744 p.
3. D.V. Paramonov, M.Y. Young, J.X. Jiang. The Flow Field in a Reactor Core and its Effect on Rod Vibration and Wear // *ASME-PUBLICATIONS-PVP*. 2001, p. 29-36.
4. S.J. King. Flow induced vibration and fretting wear in PWR fuel // *International Conference on Nuclear Engineering*. 2002, v. 35952, p. 639-648.
5. S. Davidsaver. Wear of Zircaloy-4 Grid Straps Due to Fretting and Periodic Impacting with RV Internals Baffle Plates // *Proceedings of the 15th International Conference on Environmental Degradation of Materials in Nuclear Power Systems–Water Reactors, Springer, Cham*. 2011, p. 703-718.

6. S.J. Shah, B. Brenneman. Fuel Assembly Nonlinear Dynamic Model // *International Conference on Nuclear Engineering*. 2002, v. 35952, p. 603-608.

7. D.V. Breslavsky, O.O. Chuprynin, O.K. Morachkovsky, O.A. Tatarinova, W. Pro. Deformation and damage of nuclear power station fuel elements under cyclic loading // *Journal of Strain Analysis for Engineering Design*. 2019, v. 54, issue 5-6, p. 348-359.

8. D.V. Breslavsky, O.K. Morachkovsky, O.A. Tatarinova. High-temperature creep and long-term strength of structural elements under cyclic loading // *Strength of Materials*. 2008, v. 40, issue 5, p. 531-537.

9. J. Lemaitre, J.-L. Chaboche. *Mechanics of solid materials*. Cambridge: University press, 1994, 556 p.

10. K.V. Avramov. Non-linear beam oscillations excited by lateral force at combination resonance // *J. of Sound and Vibration*. 2002, v. 257, issue 2, p. 337-359.

11. O.C. Zienkiewicz, R.L. Taylor, D.D. Wood. *The Finite Element Method for Solid and Structural Mechanics*. Butterworth–Heinemann–Elsevier, 2013, 672 p.

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МОДЕЛЮВАННЯ НАПРУЖЕНО-ДЕФОРМОВАНОГО СТАНУ ТА ЗНОШУВАННЯ У МІСЦІ КОНТАКТУ ТВЕЛУ З ТРУБНОЮ ДОШКОЮ

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Представлено підхід до ефективного розв’язання задачі прогнозування напружено-деформованого стану та зношування для випадку контакту поверхонь твелу та трубної дошки ядерного реактора. Початково-крайову пружно-пластичну постановку задачі внаслідок квазістатичного характеру вимушених коливань, який підтверджено аналізом власних частот, приведено до граничної. Розглянуто вплив неоднорідного температурного поля та змінного тиску на зовнішній поверхні оболонки твелу. Для цього було розглянуто послідовність спеціальних процедур для пошуку найбільш ефективних способів чисельного моделювання з обмеженими обчислювальними ресурсами. Методом зважених відхилів і методом скінченних різниць розв'язано задачу про нелінійні вимушені коливання при періодичному навантаженні твелу, що описується як балка при згині. Аналітичний розв’язок для переміщень оболонки твелу в задачі термопружності апроксимовано для просторового випадку та додано до загальної тривимірної моделі МСЕ. Така ж процедура була прийнята для максимальних значень амплітуди переміщень, отриманих у розв’язуванні задачі геометрично нелінійного згину балки. Після цього розв’язано загальну пружно-пластичну контактну задачу взаємодії поверхонь твелу та трубної дошки з урахуванням попередньо отриманих розподілів напружень, обумовлених доданими температурними та амплітудними переміщеннями. Як модель використано теорію пластичності ізотропного матеріалу з ізотропним зміцненням. Продемонстровано та проаналізовано межі лінійних розв’язків для прогинів балки, а також залежності прогину від часу. Наведено чисельно отримані розподіли деформацій і напружень. За отриманими максимальними значеннями напружень була зроблена спроба оцінювання зношування в зоні контакту та визначено час роботи твелу без критичного зносу під час контакту з поверхнею трубної дошки. Отримані результати можливо вважати такими, що відповідають практичним експлуатаційним даним.