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Experimental study of transverse vibrations of a fuel rod of a pulsed reactor

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In order to verify the parameters of the mathematical model of a periodic pulsed reactor and to develop the design of the active zone of a new neutron source, a vibration diagnostics stand for model fuel elements was manufactured. The work describes the structure of the stand and the tasks that are planned to be solved on it. The results of the first measurements are compared with numerical simulations. Prospects for further experiments and development of the stand's instrumentation are discussed..

Keywords: nuclear reactors, active zone, reactivity, thermoelasticity, neutrons, fuel element.

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Introduction

The Frank Laboratory of Neutron Physics is working on design engineering of a new neutron source based on a periodic pulsed reactor [1,2]. This is a fast neutron reactor cooled by liquid metal (sodium), whose core consists of neptunium nitride pellets (fissionable isotope ^{237}Np). A reactivity modulator consisting of a rotating disc made of a neutron-absorbing material is placed in close proximity to the reactor core. One of the disc sectors has a „window“ — an empty area without absorber. When the window passes near the core, the reactor switches to the prompt supercritical state, resulting in a neutron burst. Reactor pulsation frequency is equal to the modulator speed — 10 Hz. Pulse duration is about $200\,\mu$s, during which 97 % of the mean reactor power is output. Between pulses, the reactor is in subcritical state. A planned mean power of 10–15 MW and a compact core required for the maximum possible thermal neutron flow on the moderator surface (up to $10^{14}\,\mathrm{cm}^{-2}\cdot\mathrm{s}^{-1}$) lead to high heat release and significant energy release gradients within the core (about $0.01\,\mathrm{cm}^{-1}$). Together with very nonuniform energy release with time, this leads to thermoelastic strain of structural members and, consequently, to instable pulse behavior. Reactor multiplication factor is very sensitive to geometry variation, so lateral movements of fuel elements at tenths of a millimeter can induce pulse energy variation by several times [3]. The problem is in that the strain of core elements is not able to return to its initial state (typical thermal relaxation times are equal to several seconds) by the time of the next pulse, but depends on energy release in previous pulses. This results in reactivity feedback, which is difficult to control.

When selecting a core design for the new reactor, a so-called element-by-element charge layout, was proposed: several hundreds of cylindrical fuel elements are placed vertically and secured directly to the core vessel. Thus, fuel elements are mechanically isolated from each other with a gap of about 1 mm, allowing the thermoelastic strain analyses to be simplified. At a first approximation, neglecting the interaction between neighboring fuel elements through the liquid coolant, consideration of feedback is reduced to solution of a transient equation of lateral thermoelastic strain of individual fuel elements followed by calculation of additional reactivity induced by the movement of fuel pellets. Behavior of the periodic pulsed reactor considering the fuel element strain feedback was simulated in the form of a computer program [3]. It has been shown that the presence of movable structural members could lead to instable behavior [4,5]. Reactor behavior simulation results depend very much on the free vibration decay time and natural frequencies of fuel elements because energy release is periodic and can induce resonance phenomena. These stress-strain properties can be found via numerical and analytical calculations [6], however, the accuracy of such estimates is in doubt due to the structural complexity of fuel elements. Fuel element consists of many parts (Figure 1) that have a certain freedom of motion with respect to each other. Most of the mass comes on fuel pellets — about 66 %, which, despite the retaining spring pressure, can move laterally during fuel element vibrations within a gap of 0.2–0.4 mm between a pellet and the wall. Accurate numerical solution of the vibration problem for such system of many interacting bodies is impossible due to computational complexity and boundary conditions set out for pellets. Previous studies used an added mass model: instead of a fuel element, only its outer wall is considered, where mass distribution is applied to the mass of the whole fuel element accordingly. The objective of the study is to verify experimentally the above-mentioned calculations of

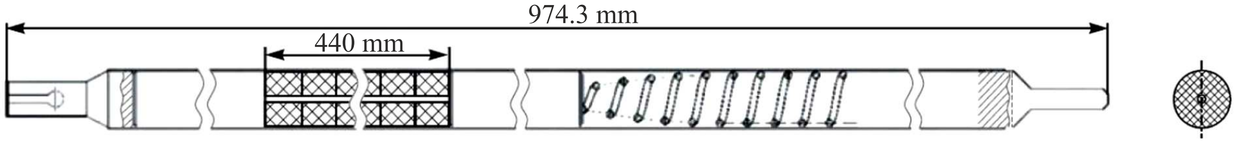

Figure 1. NEPTUN reactor fuel element drawing.

stress-strain properties (decay time and natural frequencies) and the applicability of the added mass model to the fuel element movement description.

For this, a vibration test bench was designed to measure these properties on simulated full-scale fuel elements. Besides investigating the properties of the fuel element itself and the calculation verification, the bench can be used to study hydrodynamic effects influencing the pulsed reactor operation, i.e. the effect of liquid coolant on lateral vibrations of the fuel element and interaction within a fuel element group in liquid. Experiments for investigating the effect of fuel element attachment method on dynamic properties of the pulsed reactor. This will make it possible to prove or deny the applicability of the element-by-element charge core design and to propose new design versions.

This study sets out a number of tasks for investigating a pulsed reactor fuel element, describes the bench configuration and provides measurement results. Measurements are compared with numerical simulation data. Prospects of future experiments and bench instrumentation development are discussed.

1. Problem statement

This study investigates stress-strain properties of a single fuel element for the NEPTUN reactor project [1]. Mathematical description of lateral thermoelastic strain requires natural frequencies of the first 2 or 3 harmonics and free lateral vibration decay time [3]. Rigid attachment on one end of the fuel element and freedom of movement on the other end correspond to one of the core design versions for the reactor project. This study used only this type of attachment.

The simulated fuel element is a full-scale prototype of the reactor project fuel element (Figure 1). Cylinders made of VNZh-7-3 alloy with identical size were used as fuel pellet simulators. Since the density of alloy is greater than that of neptunium nitride, there are holes in the center of simulators to provide the desired mass. Other parts of the simulated fuel element are made of 12X18H10T grade steel, unlike ChS-68ID steel used for real fuel elements. Since the density and Young's modulus of different steels are almost the same, this will not affect the experiment results.

Fuel elements consists of a casing in the form of a 18×0.4 mm steel tube with two plugs, a bottom reflector, column of 44 pellets, and retaining spring within the tube. All sizes and weight of parts, and stress-strain properties of the simulated fuel element materials correspond to the project fuel element.

The objectives of this study are to: measure the free vibration frequency of the simulated NEPTUN fuel element in air and liquid (water) at room temperature; measure the free vibration decay time of the simulated NEPTUN fuel element in the same conditions; calculate errors; compare the measurement results with numerical calculation according to the added mass model.

2. Description of the bench

The bench is designed to reproduce fuel element attachment and placement conditions as close as possible to real conditions. Therefore fuel elements are placed vertically with a predefined spacing between them (for analysis of a fuel element group), attachment assemblies are made in accordance with the project requirements and objectives of a particular experiment. Since the core vessel is a solid and rigid structure, the bench design shall also avoid abnormal vibrations during measurements.

For simulation of fuel element movement in liquid coolant, the test volume of the bench shall be filled with liquid. Liquid sodium is not applicable because it is very difficult to work with and measurements are not possible. Some liquid hydrocarbons with similar hydrodynamic properties (hexane, acetone, propanal, etc.) can be used as a coolant simulator, however, not all of them are suitable for experiments for safety reasons [7]. Water differs considerably from liquid sodium in its properties (density and viscosity), but is the most easily available and suitable material. Therefore, the first bench measurements were performed in water with subsequent consideration of high viscosity. To avoid corrosion, bench components exposed to water are made of stainless steel and aluminum alloy.

Instruments and other equipment that will be placed in various locations near the simulated fuel elements require considerable space and immediate access for removal and installation. Taking this into account, the steel enclosure has a sufficient width (diameter 550 mm), the top frame plate is notched. The enclosure is removable.

At this stage, the vibration test bench (Figure 2) consists of a solid steel plate, which serves for support and avoids abnormal vibrations, an aluminum frame for fuel element attachment and other equipment. Two aluminum sections

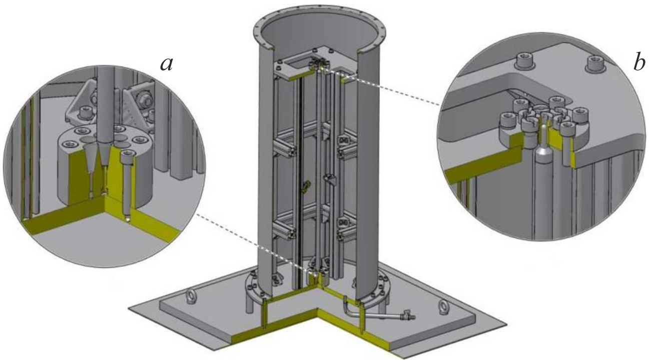

Figure 2. Fuel element vibration test bench drawing: *a* — bottom attachment, *b* — top attachment.

are placed on the frame parallel to the fuel elements and are designed for sensor mounting.

The top and bottom attachments have replacement mounting sleeves to examine different fuel element attachment methods and to mount up to seven fuel elements simultaneously.

3. Measuring instruments

The choice of a sensor to be used at the bench is driven by a particular task, measurement conditions and user-friendliness. Strain gauge, optical, electromagnetic, piezoelectric or capacitance type sensors can be used to detect lateral vibrations of the rod [8]. Considering that this work implies only relative measurements of strain amplitude and water medium conditions, Tesla's Corona-4SC electromagnetic sensor designed for musical instruments was chosen. It features a sufficient sensitivity to ferromagnetic items at distance of several millimeters, a sealed housing and low cost. This is a proximity sensor, which is especially important for measuring fuel element vibrations. Connection of additional devices or wires to the fuel element can distort measurements.

Electric signal at the sensor output recorded by the Hantek 6022BL oscilloscope and sent to computer via USB interface. The oscilloscope has two channels, and this feature was used for sensor calibration.

The sensor consists of a multiturn winding on a permanent magnet core. When a ferromagnetic item moves near an open part of the magnetic circuit, magnetic flux through the winding varies, inducing EMF at the winding ends. It follows from the operating principle of the sensor that due to the law of electromagnetic induction, EMF at the sensor outlets shall be proportional to the test item velocity. With exponential decay of sinusoidal vibrations, the velocity decay time constant and amplitudes are equal

$$v(t)=\frac{\partial x}{\partial t}=\frac{\partial}{\partial t}\left(e^{-t/\tau}\cos\omega t\right)=-e^{-t/\tau}\left(\frac{\cos\omega t}{\tau}+\omega\sin\omega t\right).$$

Therefore the sensor can be used for measuring free vibration decay time of the fuel element in linear response mode. To verify the linear ratio of the velocity and EMF, calibration was performed at the sensor output. It included signal amplitude measurement when an item moved at a known velocity near the sensor. Metal ball rolling over an inclined surface passed two sensors spaced at a known distance. The detected EMF signal looks as shown in Figure 3. Time interval between events *2* and *5* was used to calculate the mean velocity $\overline{v}$ of movement between the sensors. Interval t_1 between extrema *1*–*3* and interval t_2 between extrema *4*–*6* were also calculated. After this, the instantaneous velocity v of the ball passing by the second sensor was calculated using equation.

$$v=\frac{2\overline{v}}{1+t_2/t_1}.$$

The use of two sensors for calibration as mentioned above makes it possible to consider nonuniform motion on an inclined surface. The first sensor in this case serves only to determine times *1*–*3*.

Then the EMF amplitude $U_{\max}$ of the second sensor between extrema *4*–*6* was measured. As a result, the amplitude–velocity ratio was measured for the second sensor and obeys the linear law within the errors (Figure 4). Inaccuracy of determination of the positions of points on the signal curve is the main source of error due to electronics noise.

Linear dependence of EMF on the item velocity makes it possible to use the sensor for measuring the decay time at constant free frequency of vibrations (amplitude frequency response of the sensor was not measured), which completely satisfies the objectives of this work. Accuracy of vibration frequency measurement is defined by sensor sensitivity, noise level and oscilloscope time resolution.

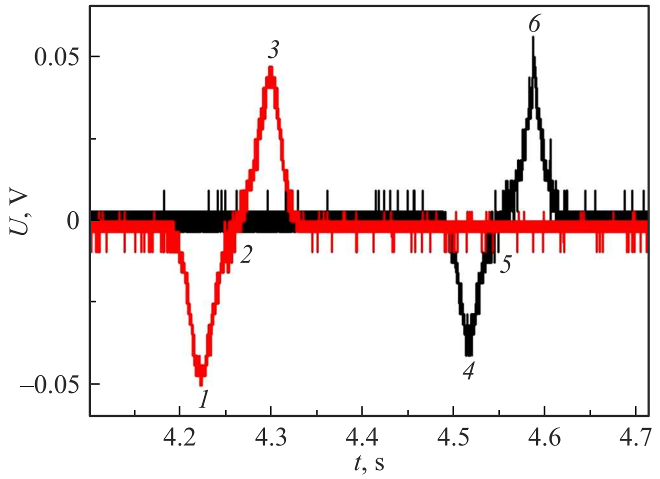

Figure 3. Signal from the first (red line) and second (black line) sensors transmitted through a metal item. Numbers show extrema and zero crossing points.

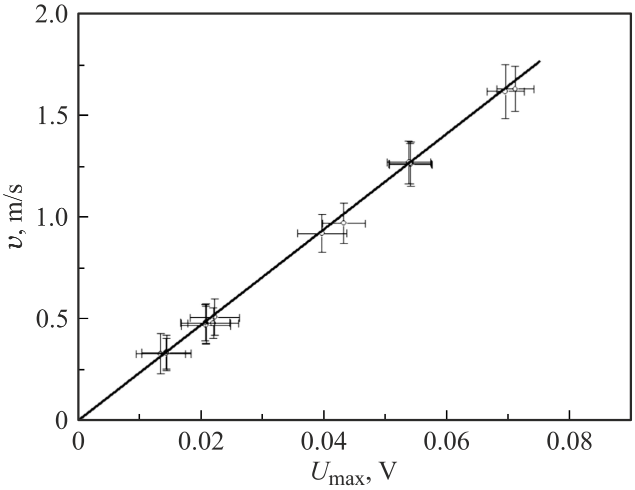

Figure 4. Item velocity vs. EMF of the second sensor. Points — experiment, line — linear approximation.

4. Measurement of natural lateral vibration frequencies of the fuel element

Recording of damped free vibrations is one of the methods for natural vibration measurement. Fuel element movement is described by the following expression [9]:

$$y(x,t) = e^{-t/\tau} \sum_{k=1}^{\infty} A_k W_k(x) \cos(2\pi \nu_k t + \varphi_k),$$

where $y(x,t)$ — is the lateral misalignment of the fuel element at point x at time t, τ is the vibration decay time, k is the harmonic number, A_k is the initial amplitude, $W_k(x)$ is the eigen (beam) function of the fuel element, ν_k is the natural frequency, φ_k is the initial phase. A_k and φ_k are set as initial conditions at vibration excitation time: the fuel element shape and speed at $t = 0$ correspond to them. From an experiment standpoint, it would be advisable to excite free vibrations of only one k-th harmonic, whose frequency shall be measured ($A_k \neq 0$, $A_{i \neq k} = 0$). It is not technically feasible. However, when the form of functions $W_k(x)$ is known, the most suitable excitation method can be chosen. This may be a deviation from equilibrium or impact at a certain point of a fuel element.

A simulated fuel element was placed on the bench and rigidly secured at the bottom with full freedom on the top (top attachment is removed). The sensor was placed at the top plug of the fuel element (Figure 2), which provided the largest signal amplitude. To measure the natural frequency of the first harmonic, free vibrations were excited mechanically by deviation of the top end of the fuel element from equilibrium. This is explained by the fact that the fuel element curvature in this position is the nearest to the eigenfunction $W_1(x)$ of the first harmonic. Example of the received signal is shown in Figure 5.

Fundamental frequency of the received signal can be measured by building the signal spectrum or by counting the number of vibrations during a sufficiently long time period. The latter is more accurate in this case and give the first harmonic frequency in air (8.07 ± 0.04) Hz. Estimation of errors considered statistical errors (a series of measurements with different sensor positions was performed) and signal maximum position measurement errors.

For predominant excitation of the second harmonic, an impact was made by a solid item against the fuel element at a distance equal to 1/3 of the height from the bottom end. The second eigenfunction of the fuel elements $W_2(x)$ has its maximum at this point. Example of the received signal is shown in Figure 6.

Measurement of the second harmonic frequency in air gives (39.1 ± 0.6) Hz. The frequency and error calculation method is similar to the previous case. Error of measurement of the second natural frequency is higher than that of the first one. This is explained by a l,ow vibration amplitude

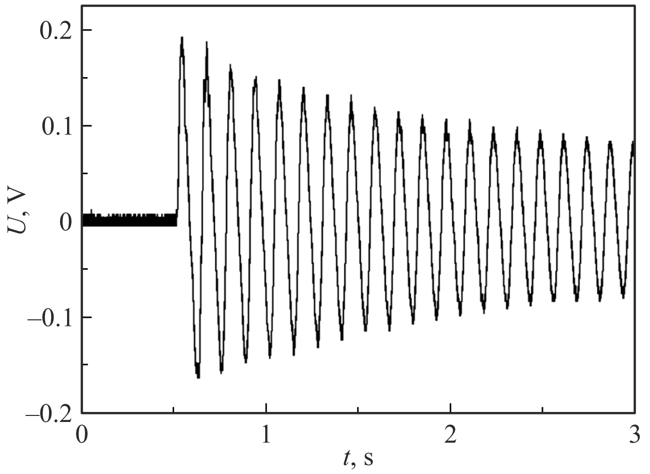

Figure 5. Signal with free vibrations in air. Excitation by deviation from equilibrium.

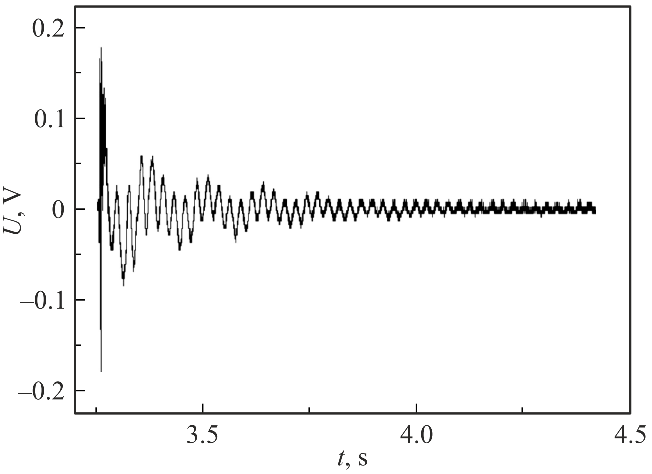

Figure 6. Signal with free vibrations in air. Excitation by impact against the fuel element casing.

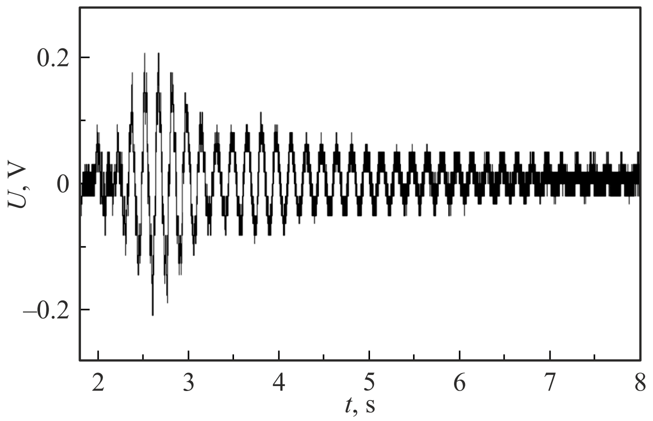

Figure 7. Signal with free vibrations in air. Excitation by deviation from equilibrium.

and short decay time, which is described below. It was not possible to measure the third harmonic frequency by the free vibration method in air.

For measurement in liquid, the bench enclosure was filled with water. Measurements were performed similar to the measurements in air. Only the first harmonic frequency was measured. Example of the received signal is shown in Figure 7.

Measurement of the first harmonic frequency in water gives (6.3 ± 0.1) Hz.

5. Measurement of free vibration decay time

To determine the free vibration decay time of the fuel element in air, positions of maxima on the curve in Figure 5 were determined. Since the obtained points are poorly approximated by $\exp(-t/\tau)$, it is suggested that each harmonic has its own decay time (validity of such assumption is discussed in Section 7). Vibration amplitude variation with time was found from the second harmonic measurement signal curves (Figure 6), the obtained points were approximated by $\exp(-t/\tau_2)$ (Figure 8). τ_2 was equal to (0.3 ± 0.1) s.

After this, points of maxima on the curve in Figure 5 were approximated by $A_1 \cdot \exp(-t/\tau_1) + A_2 \cdot \exp(-t/\tau_2)$, and the first harmonic decay time τ_1 was found (Figure 9). It was equal to (4.3 ± 0.9) s.

According to the measurements, fuel element vibrations in water are more complex and require that hydrodynamic effects be considered (liquid waves in the enclosure). Vibration amplitude variation with time (Figure 7) makes it possible to evaluate the decay time in liquid as (2.0 ± 0.5) s.

Analysis of errors has shown that electronics noise and random errors are the main sources of errors.

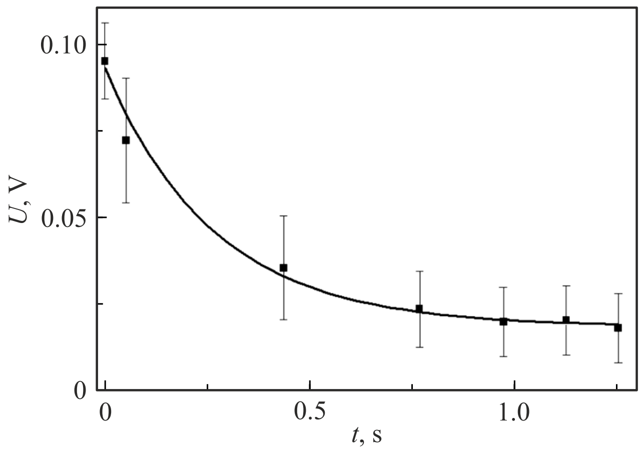

Figure 8. Variation of the second harmonic amplitude in air with time. Points — experiment, line — approximation.

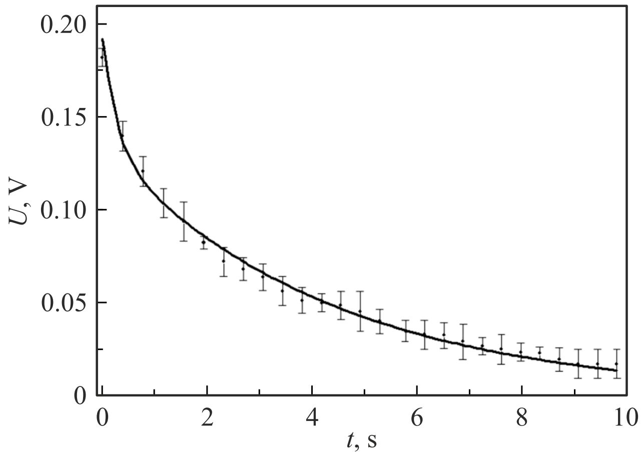

Figure 9. Free vibration maxima variation of the fuel element with time. Points — experiment, line — approximation.

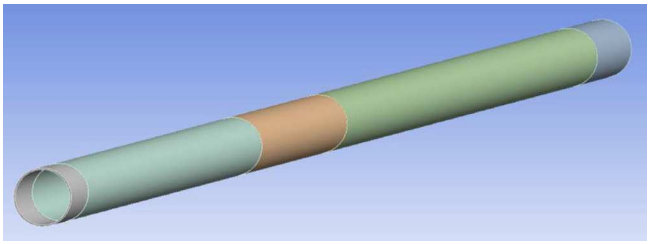

Figure 10. Calculated fuel element geometry.

6. Numerical simulation

Three natural frequency calculation methods are described in [6,10] for the NEPTUN fuel element according to the added mass model in simplified geometry. Finite element method of numerical calculation in the adjusted geometry of the fuel element was chosen for experiment simulation (Figure 10). The computational model is a hollow tube 18 mm in diameter, consisting of five sections with different density, corresponding to the region of the bottom reflector, fuel pellets, top reflector, spring and top plug. Boundary condition involved rigid fixation of the bottom end of the tube.

Modal analysis has found frequencies and forms of the first two harmonics. Calculations have shown that natural frequencies depended on the fuel element wall thickness to a great extent. Since the wall thickness tolerances of the simulated fuel element are ± 0.07 mm, the wall thickness for the calculated geometry was set to 0.45 mm according to the equality of the first harmonic frequency to the experimentally measured frequency of 8.07 Hz. The calculated second harmonic in this case was equal to 35.87 Hz, which is lower than the experimental value of (39.1 ± 0.6) Hz.

7. Discussion of findings

The chosen type of sensor and measurement method made it possible to determine the first and second natural frequencies of the simulated fuel element with a relative error of about ± 1 %, and the free vibration decay time with a relative error of $\pm 20\,\%-30\,\%$. This is sufficient for the purposes and objectives of this study. Numerical simulation has identified that the natural frequency depended on the fuel element wall thickness to a great extent. It can be suggested that frequencies of individual fuel elements differ significantly. This fact, which is to be confirmed experimentally, can be treated as a positive phenomenon because it reduces the probability of collective synchronous vibrations of fuel elements [3].

Despite a low accuracy of decay time measurement, the experiments provide substantial information for investigating the reactor behavior because friction effects in complex mechanical systems are not easy to be calculated numerically and analytically. Vibrations decay in air due to internal friction of fuel element components, mechanical energy in water also dissipates through interaction with liquid. The fact that water has twice as high viscosity as liquid sodium [11] (with a comparable density) makes it possible to estimate the vibration decay time of a single fuel element in sodium from 2 to 4 s. Vibration energy dissipation processes of a group of fuel elements immersed in liquid are apparently more complex and require additional experiments.

The added mass model used in numerical and analytical calculations [6,10] leads to certain discrepancies between theoretical and experimental results: overestimated theoretical second harmonic frequency and equal theoretical decay times of different harmonics. Difference in natural frequencies can be explained by pellet movement within the fuel element with respect to the shell at high velocities, which reduces the effective added mass. Difference in the first and second harmonic decay times is explained by a complex origin of friction (internal friction with fuel element strain, friction of individual structural components, interaction with liquid) and by a simplified representation of the friction force in equations of motion [3,9]. Thus, the added mass model in its initial form cannot be used in further calculations and requires modification. Measured parameters can be included in the design model in the form of corrections for mathematical simulation of reactor behavior. For the given type of fuel element attachment (free top end), the first two harmonics are sufficient to describe fuel element movement in the core (higher harmonic frequencies differ very much from the reactor pulsation frequency and don't affect the reactor behavior).

Since fuel element vibrations in the pulsed reactor are a negative phenomenon, future work on the vibration test bench shall be focused on finding the best fuel element attachment method where the first harmonic frequency could be as far as possible from the reactor pulsation frequency, and the free vibration decay time and amplitude would be the lowest. Moreover, the attachment shall meet the main reactor core requirements: possibility to remove a fuel element from the core and freedom of axial elongation during heating. Frequency and decay time measurements are also intended to be performed for a group of seven fuel elements immersed in liquid.

Future experiments on the bench apparently require that other type of sensors be used. Study of the behavior of a group of fuel elements implies that the movement of individual fuel elements is measured. electromagnetic sensors are not suitable because of high sensitivity to the movement of adjacent items. In addition, measurement of natural frequencies with different types of attachment may require another method because free vibrations of the first harmonic have a small amplitude and are poorly detectable. A forced vibration method where a fuel element is exposed to an external periodic (mechanical or electromagnetic) force is also incompatible with this type of sensors that are very sensitive to noise.

Areas of future work on the experimental bench also include investigating the effect of a turbulent liquid flow on fuel element movement, simulation of heat shock using a magnetic field and permanent bending with nonuniform heating of the fuel element.

Conclusion

The first measurements of fuel elements on the vibration test bench provided adjusted values of properties necessary for the periodic reactor behavior model. It is shown that the added mass model is not applicable for accurate description of fuel element vibrations and needs to be adjusted. Measurement accuracy and provisions for installation allow the model to be used for design of an optimized core for the new neutron source.

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Conflict of interest

The author declares no conflict of interest.

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