TECHNICAL UNIVERSITY OF CLUJ-NAPOCA

ACTA TECHNICA NAPOCENSIS

Series: Applied Mathematics, Mechanics, and Engineering
Vol. 67, Issue II, June, 2024

TRANSMISSIBILITY ANALYSIS TO INTERACTION CHAMBER OF THE ELI-NP PROJECT ARCHITECTURE FOR THE ELIADE DETECTOR SYSTEM

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Abstract: *The paper aims to do a study on the forced vibrations of the components inside the interaction chamber for the gamma ray beam from the ELI-NP Bucharest research facility. For this, the transmissibility of vibrations from the ground to the parts inside the interaction chamber is studied and, in particular, on the target support. The research is necessary because experiments with gamma rays focus on targets that can sometimes be very small and any deviation and uncontrolled movement of the target can lead to the failure of the experiment. Based on the results obtained, it is proposed to increase the rigidity of the target support in order to decrease the transmissibility of excitations ground at the target.*

Key words: *vibration, transmissibility, ELI-NP, detector, Interaction Chamber,eigenfrequency*

1. INTRODUCTION

The paper presents a study carried out on the dynamic behavior of the interaction chamber (CI) for the ELI-NP particle detector (*Extreme Light Infrastructure-Nuclear Physics*) under the action of a harmonic excitation applied to the base.

The transmissibility of vibrations on the interaction chamber (CI) where the target that will be subjected to gamma ray bombardment is located will be studied[1-3] .

The inertial platform, on which all the research systems and equipment are placed, is made of a reinforced concrete block, consisting of two parts. The first block, which we call the main part, has a thickness of 1.5 m. The other block (the secondary part) has a thickness of 0.6 m.

Obviously, in a vibration analysis of the entire system, the deformability of the concrete blocks becomes important and it, the 54,000-ton concrete platform suffering deformations that must be taken into account in a more careful calculation [4,5]. Only in this way can results be obtained for the extremely precise experiments that will take place on this platform.

The massive concrete block is placed on a spring system made up of about 1000 spring batteries. These batteries can be activated, so as to ensure an elastic suspension or they can be deactivated, ensuring a rigid connection between the platform and the ground. In this way, the distribution of the weight of the platform on the ground can be changed.

Each of the batteries of springs that support the platform contains between 3 and 7 springs, between which there are damping elements. So the spring batteries also have a role as shock absorbers [6,7].

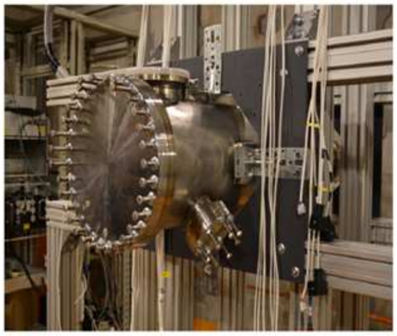
Inside the IC in **Fig.** 1, reactions occur between the right beam of gamma rays and various materials from which the target that is touched by them is designed, and the role of the IC is to keep this beam hitting the target as precisely as possible for as long as possible.

Several detection systems are provided around the IC to monitor the nuclear reactions occurring inside the IC. They are fixed with high precision relative to the IC considered as a reference.

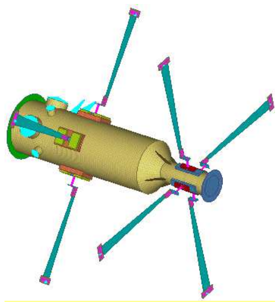
In addition to tracking the gamma ray beam it is necessary to determine with great precision the relative position between the

Received: 30.04.24; **Similaritie**s: 29.05.24: **Reviewed**: 10.06./10.06.24: **Accepted**:20.06.24.

sample holder placed (placed on the target of gamma ray inside the IC) and the battery of detectors.



a.



b.

Fig.1. Interaction room: a) real model, b) virtual model,

The precision required for a gamma-ray experiment is influnced by the dimension of the target. For an experiment, accuracy is considered to be satisfactory for a value of 2 **μ**m. In general, the gamma beam produced by the high-power ELI-NP laser system shows slight fluctuations in intensity and direction [8,10]. The study of such problems can be analyzed using methods developed recently, through models that use the possibilities offered by modern computing techniques [11-16].
In the paper, the authors propose the analysis of transmissibility in amplitude from an excitation of the ground or IC to the target located at the end of an elastic support.

2. MODELS AND METHODS

In the work, the IC kinematics and relative motion of different parts and components of the mechanical systems inside the IC will be studied. The best method to do this is the use of Finite Element Method (FEM). So, it is possible to determine the field of stress and strain in different parts of the IC but it is also possible to made a study of the vibration of the entire mechanical system as a whole [17,18]. Fig**.** 2 shows the finite element model (FEM) [19-21].

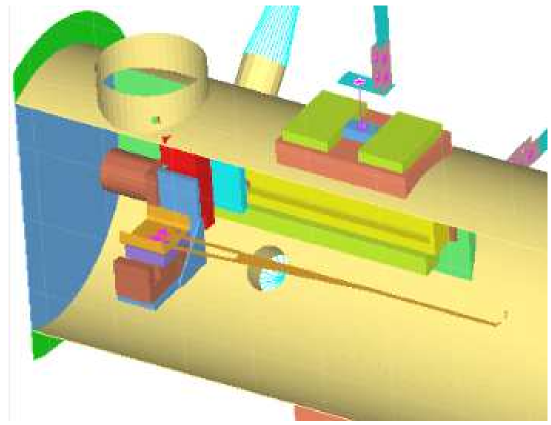


Fig. 2 – Finite element model (FEM) of the interaction chamber

Based on Lagrange's equations, which assume the knowledge of the energies in the system, it will be possible to make estimates related to the eigenmodes of the entire system to be analyzed, respectively of the transmissibility which represents the ratio between the quantity leaving the system and the quantity entering the system.
For a conservative system, in free vibration, the generalized forces Q_j are the derivatives with changed sign of the potential energy W_p of the system, with respect to the generalized coordinates q_j [22,23]:

$$Q_j = -\frac{\partial W_p}{\partial q_j} \quad ; \quad j = \overline{1,n} \ . \qquad (1)$$

In this case, Lagrange's equations can be applied using the form:

$$\frac{d}{dt}\left(\frac{\partial W_c}{\partial \dot{q}_i}\right) - \frac{\partial W_c}{\partial q_i} + \frac{\partial W_p}{\partial q_i} + \frac{\partial W_d}{\partial \dot{q}_i} = 0ș; \quad j = \overline{1,n} \ , \qquad (2)$$

where W_c is the kinetic energy, W_p the potential energy, W_d the energy dissipated in the system, q_j the generalized coordinate of each degree of freedomm, and $\dot{q}_i$is the generalized velocity of each degree of freedom [24-27].

In general matrix form, these energies can be written as:

$$W_c = \frac{1}{2}\{\dot{q}\}^T[m]\{\dot{q}\} \quad ;$$
$$W_p = \frac{1}{2}\{q\}^T[k]\{q\} \quad ;$$
$$W_d = \frac{1}{2}\{\dot{q}\}^T[c]\{q\} \quad . \tag{3}$$

The matrices [m], [c] and [k] are symmetric matrices, and the vectors of generalized coordinates and generalized velocities are column vectors of the type:

$$\{q\} = \begin{Bmatrix} q_1 \\ q_2 \\ \vdots \\ q_n \end{Bmatrix} \quad ; \quad \{\dot{q}\} = \begin{Bmatrix} \dot{q}_1 \\ \dot{q}_2 \\ \vdots \\ \dot{q}_n \end{Bmatrix} \quad . \tag{4}$$

By substituting (3) into (2) the general form of the equations characterizing the free vibrational motion of the damped system will be obtained.

$$[m]\{\ddot{q}\} + [c]\{\dot{q}\} + [k]\{q\} = \{0\} \quad . \tag{5}$$

To determine the eigenmodes of free vibrations, the equation is written:

$$\{\ddot{q}\} + [d]\{q\} = \{0\} \quad , \tag{6}$$

where $[d]$ is the dynamic matrix given by the relation:

$$[d] = [m]^{-1}[k] = [m]^{-1}[\delta]^{-1} \quad , \tag{7}$$

where $[\delta]$ is the matrix of influence coefficients.

The solutions of the system (6) is:

$$\{q\} = \begin{Bmatrix} a_1 \\ a_2 \\ \vdots \\ a_n \end{Bmatrix} \sin(pt+\varphi) = \{a\}\sin(pt+\varphi). \tag{8}$$

Substituting (8) into (6) yields:

$$\left([k] - p^2[m]\right)\{a\} = \{0\} . \tag{9}$$

The natural circular frequency p_j^2, from (9) will be determined from the condition:

$$\det\left([k] - \lambda_j[m]\right) = 0 \; ; j = \overline{1,n} \, , \tag{10}$$

where $\lambda_j = p_j^2$ represent the eigenvalues of the system.

Each determined eigenvalue λ_j corresponds to a vector $\{a^{(j)}\}$ called an eigenvector with real elements $a_r^{(j)}$ that satisfies the matrix equation:

$$\left([k] - \lambda_j[m]\right)\{a^{(j)}\} = \{0\} . \tag{11}$$

The normalization calculation of the elements of the vector $\{a^{(j)}\}$ will be based on (12) :

$$\mu_r^{(j)} = \frac{a_r^{(j)}}{a_1^{(j)}} . \tag{12}$$

It is noted:

$$\{a^{(j)}\} = \begin{Bmatrix} a_1^{(j)} \\ a_2^{(j)} \\ \vdots \\ a_n^{(j)} \end{Bmatrix} = a_1^{(j)} \begin{Bmatrix} 1_1^{(j)} \\ \mu_2^{(j)} \\ \vdots \\ \mu_n^{(j)} \end{Bmatrix} = a_1^{(j)}\{\mu^{(j)}\}, \tag{13}$$

where $\{\mu^{(j)}\}$ is the normalized eigenvector of the eigenmode *j*.

The motion in the eigenmode of vibration of order *r* is characterized by the vector:

$$\{q^{(j)}\} = \{a^{(j)}\}\sin(pt+\varphi) = a_1^{(j)}\{\mu^{(j)}\}\sin(pt+\varphi) = \eta_j\{\mu^{(j)}\} \tag{14}$$

where the main coordinate *j* was denoted by η_j:

$$\eta_j = a_1^{(j)} \sin(pt+\varphi) \quad . \tag{15}$$

The motion of the system is given by a superposition of eigenmodes and can be expressed as:

$$\{q\} = \sum_{j=1}^{n} \eta_j \left\{\mu^{(j)}\right\} = [A]\{\eta\} \quad . \tag{16}$$

Here the matrix [A] is called the modal matrix or the normalized eigenvector matrix and has the normalized eigenvectors as columns, and $\{\eta\}$ is the column matrix of the principal coordinates. Equation (16) represents the transformation to modal coordinates.

$$[A] = \left[\left\{\mu^{(1)}\right\} \quad \left\{\mu^{(2)}\right\} \quad \ldots \quad \ldots \quad \left\{\mu^{(n)}\right\}\right] = \\ = \begin{bmatrix} 1 & 1 & \ldots\ldots & 1 \\ \mu_2^{(1)} & \mu_2^{(2)} & \ldots\ldots & \mu_2^{(n)} \\ \vdots & \vdots & \vdots\vdots & \vdots \\ \mu_n^{(1)} & \mu_n^{(2)} & \ldots\ldots & \mu_n^{(n)} \end{bmatrix} \quad . \tag{17}$$

Using the coordinate transformation (16), equation (6) becomes:

$$[M]\{\ddot{\eta}\} + [K]\{\eta\} = \{0\} \quad . \tag{18}$$

With [M] is denoted the modal mass matrix and with [K] the modal stiffness matrix. These matrices have the expressions:

$$\begin{aligned} [M] &= [A]^T [m][A] \quad ; \\ [M] &= [A]^T [m][A] \quad . \end{aligned} \tag{19}$$

The influence coefficients of the generalized modal mass will be calculated using the generalized modal masses on the main diagonal of the matrix [M] according to (1.50) [28]:

$$\alpha_{ii} = \frac{1}{\sqrt{M_{ii}}} \quad . \tag{20}$$

The matrix of eigenvectors obtained by transforming into modal coordinates, which will be used in the calculations for the forced response, is:

$$[\Phi] = [A][\alpha] = \begin{bmatrix} 1 & 1 & \ldots\ldots & 1 \\ \mu_2^{(1)} & \mu_2^{(2)} & \ldots\ldots & \mu_2^{(n)} \\ \vdots & \vdots & \vdots\vdots & \vdots \\ \mu_n^{(1)} & \mu_n^{(2)} & \ldots\ldots & \mu_n^{(n)} \end{bmatrix} \times \\ \times \begin{bmatrix} \alpha_{11} & 0 & \ldots & \ldots & 0 \\ 0 & \alpha_{22} & \ldots & \ldots & 0 \\ \vdots & \vdots & \ddots & \vdots & \vdots \\ & & & \ddots & \\ 0 & 0 & \ldots & \ldots & \alpha_{nn} \end{bmatrix} \quad . \tag{21}$$

The eigenvectors, in modal coordinates, are considered correctly determined if the matrix of generalized modal masses $[\hat{m}]$ is a unity matrix, and the matrix of generalized modal stiffnesses contains the eigenvalues λ_j on the main diagonal . The computation of these generalized modal matrices is given in (17).

$$[\hat{m}] = [\Phi]^T [M][\Phi] = [I] \quad ; \\ [\hat{k}] = [\Phi]^T [m][\Phi] = \begin{bmatrix} \lambda_1 & 0 & \ldots & 0 \\ 0 & \lambda_2 & \ldots & 0 \\ \vdots & \vdots & & \vdots \\ 0 & 0 & \ldots & \lambda_n \end{bmatrix} \quad . \tag{22}$$

To determine the modal participation factors , respectively the effective modal mass for each mode, an influence matrix is defined $\{\bar{r}\}$ that represents the mass displacements resulting from static displacements and rotations of the unit value base. For example, for a massive body in space that has 6 degrees of freedom (three translations and three rotations), this influence matrix is a unity matrix, if we consider the center of gravity as the reference point.

$$[\bar{r}] = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix} \quad . \qquad (23)$$

The vector of influence coefficients for each eigenmode is calculated with the relation:

$$[L] = [\Phi]^T [M][\bar{r}] \quad . \qquad (24)$$

The modal participation factors will be given by the relation [29-32]:

$$\Gamma_j = \frac{L_j}{\hat{m}_j} \quad . \qquad (25)$$

The effective modal mass is:

$$m_{eff,j} = \frac{L_j^2}{\hat{m}_j} \quad . \qquad (26)$$

To study the response of the structure under an excitation in the base, equation (5) is written in the form:

$$[m]\{\ddot{q}\} + [c]\{\dot{q}\} + [k]\{q\} = -[m]\{r\}\ddot{q}_b \ , \qquad (27)$$

where, [m] is the mass matrix (nxn), [k] – the stiffness matrix (nxn), [c] – the damping matrix (nxn), {r } – the vector of influence coefficients for eigenmode j (nx1), $\ddot{q}_b$ - the acceleration of base.

By applying the transformation to modal coordinates and multiplying to the left by $[\Phi]^T$, equation (27) becomes:

$$[\Phi]^T[m][\Phi]\{\ddot{\eta}\} + [\Phi]^T[c][\Phi]\{\dot{\eta}\} + +[\Phi]^T[k][\Phi]\{\eta\} = -[\Phi]^T[m]\{r\}\ddot{q}_b \ . \qquad (28)$$

Equation (28) can be reduced to the form:

$$\ddot{\eta}_j + 2\xi_j p_j \eta_j + p_j^2 \eta_j = -\Gamma_j \ddot{q}_b \ , \qquad (29)$$

where, η_j – modal displacement of mode j, ξ_j – modal critical damping fraction of mode j.

The maximum modal response in displacement is calculated with the relation:

$$\eta_j = \Phi_j \cdot \Gamma_j \cdot S_d(\xi_j, f_j) \quad . \qquad (30)$$

3.RESULTS

In order to carry out the analysis of vibrations and transmissibility, FEM was used in two stages. In the first stage, the eigenfrequencies and eigenmodes of movement of the IC were determined, and in the second, the transmissibility was determined.

Determining the eigenmodes is necessary because inside the IC there are electric motors that can become, for the frequencies found, an important disturbing source. If we have determined what the natural frequencies are and we have determined what the transmissibility of the system is, an applied study can be done to determine the deviation of the target from the ideal position, in different cases of excitation coming from outside the system.

Of course, depending on the dimensions of the target, the experimenter can decide whether the deviation is important or not in **an** experiment.

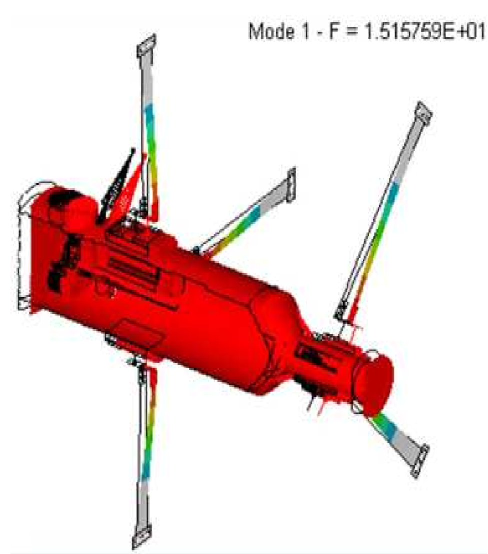


Fig. 3. Eigenmodes 1 for the IC

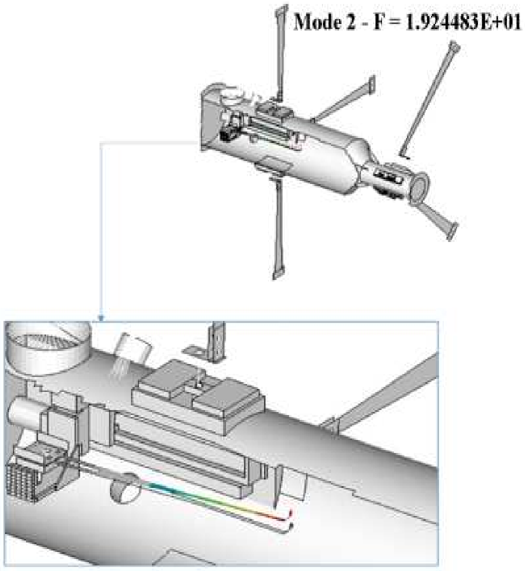


Fig.4. Eigenmode 2 for the IC

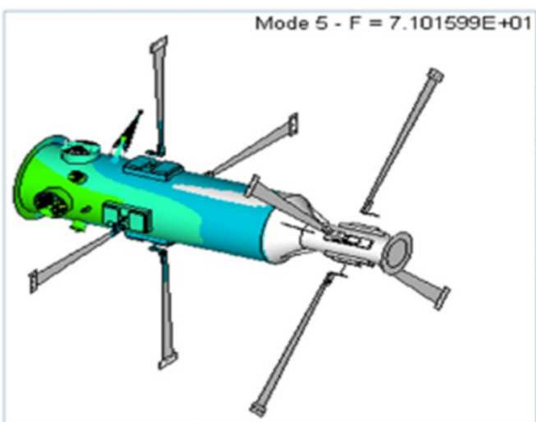


Fig. 5. Eigenmode 5 for the IC

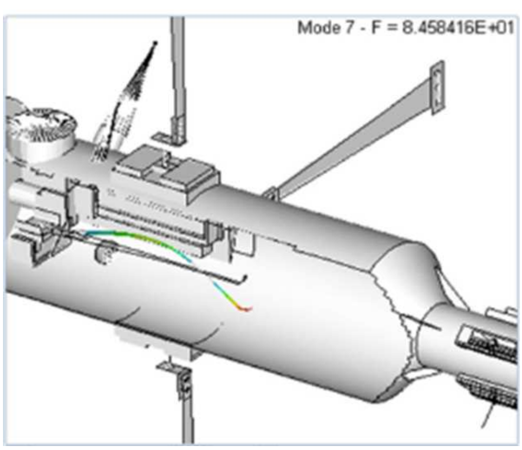


Fig. 6a. Eigenmode 7 for the IC

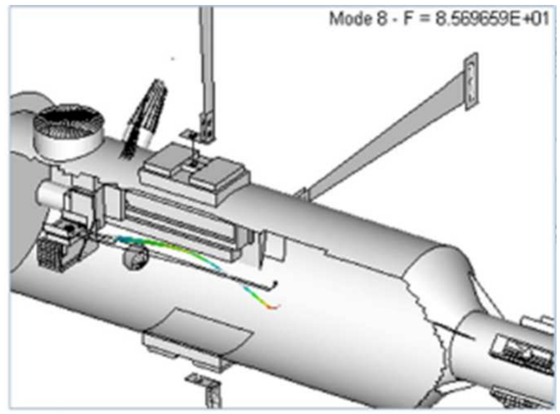


Fig. 6b. Eigenmode 8 for the IC

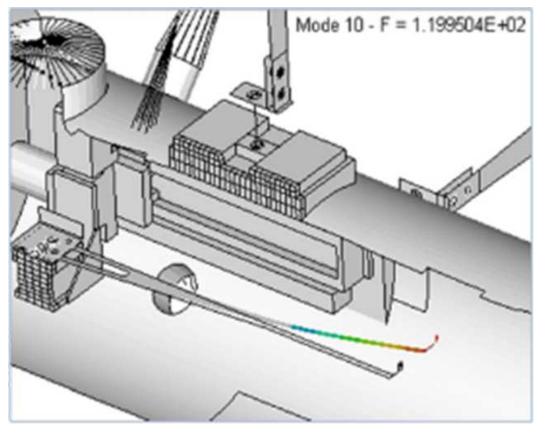


Fig. 7– Eigenmode 10 for IC

Figures 8-9 show the form the amplitude for different eigenfrequencies of excitation that can bring an input of influence on the transmissibility of the system which involves relating the output quantity (target displacement) to the input quantity (harmonic excitation of the base with unit amplitude).

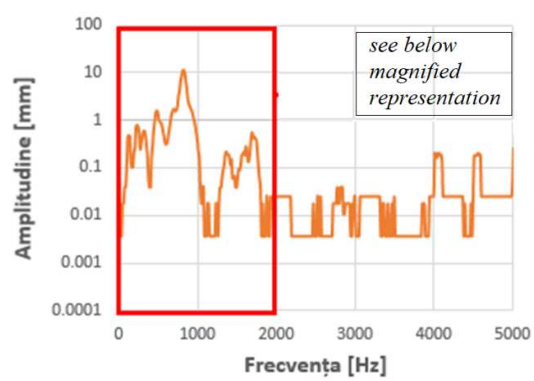


Fig.8. Transmissibility of the vibration to target of IC

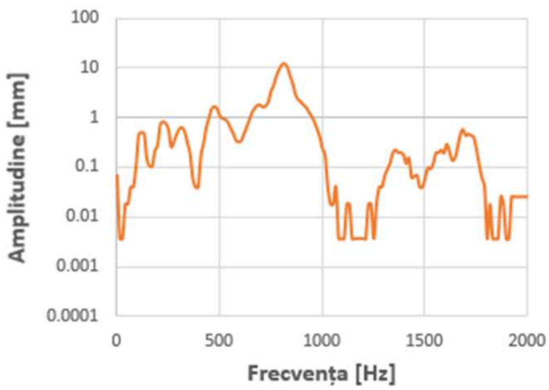


Fig. 9. Magnified range 1000-2000 Hz

The amplification factor obtained from the transmissibility analysis is presented in Figs. 4,5. In the analysis carried out on a range of values between 0 and 5000 Hz, it is found that the frequencies that can be harmful are placed in the range 0-2000 Hz. Within this range, it is found that for some excitation frequencies, a 13-fold amplification of the target amplitude compared to the excitation amplitude can be obtained. This happens for the frequencies induced by electric motors. This result implies that problems may arise in the experiments related to the fact that the target may, due to vibrations, get out of the way of the gamma ray beam. To reduce this transmissibility, one way would be to increase the rigidity of the target support. Another solution that can be applied is to introduce a damping system (however, this solution is difficult to apply due to the need for a suitable space inside the IC). The solution that was proposed is to change the shape of the target support with a ribbed surface. In this way, the stiffness of the support can be increased accordingly with minimal expenses. Changing the material of the support to increase the rigidity can be risky because the response of the material must be taken into account in the case of the action on it of a beam of gamma rays of such intensity.

4. DISCUSSION AND CONCLUSIONS

The IC response of the ELI-NP project to the harmonic excitations of the base produced by anthropic activities or natural phenomena was studied in the work. Knowing the transmissibility of ground vibrations at the IC and implicitly at the target allows the appreciation of the good functioning of the entire system and the fulfillment of the proposed test program.

Obviously, the foundation is designed to be a good isolation both against external, anthropogenic and natural vibrations, which may appear but also against the vibrations produced by the existing equipment and installations within the laboratory and whose operation could negatively influence the accuracy of the measurements made inside IC. Obviously, there is always the danger of the occurrence of predictable and unpredictable vibrations that are transmitted to the IC. To move the target inside the IC, there are three independent systems that allow the target to position itself precisely in the path of the gamma ray beam. And these actuators can be generators of vibrations in the entire system and if the excitation frequency is in the resonance area of the system, the excitations produced can be amplified.

The work proposed an analysis of the way in which the vibrations that can appear in different components of the IC can finally be transmitted to the target on which the main flow of gamma rays will be directed. Based on the proposed model and the study undertaken, it is found that there can be a 13 times amplification of the amplitudes of the target vibrations at a harmonic excitation of the soil of unit amplitude.

The phenomenon of this significant amplification occurs at a frequency around 790 Hz. It is obvious that this frequency should be avoided. The experimental measurements carried out within the ELI project showed that the motors of the actuators induced excitations outside the range in which this frequency is found.

There are other frequencies that must be avoided but that do not lead to such a dramatic amplification of the target amplitude (see Fig. 9). Due to this amplification of the vibrations, it may be possible for the target to suffer a significant displacement so that the gamma rays act outside the target and the experiment fails. For this reason, a concrete study of vibrations, within each experiment and model of the bar that supports the target, which also takes into account the dimensions of the target, is required to obtain correct results in the experiments that will be carried out within the ELI-NP program .

Consequently, a resizing of this device with a fixation system may be necessary so that ground-to-target transmissibility decreases. Also, a lever shape modification based on shape optimization and material distribution methods could be a smart viable solution to eliminate the shortcomings related to resonance area vibrations.

Also, as mentioned, the choice of material must be made in such a way that physical characteristics are not affected by the gamma ray beam inside the CI.

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Analiza transmisibilității în camera de interacțiune a proiectului ELI-NP arhitectura sistemului detector ELIADE

Rezumat. *Lucrarea isi propune sa faca un studiu asupra vibratiilor fortate ale componentelor din interiorul camerei de interactie pentru fascicolul de raze gamma de la facilitatea de cercetare ELI-NP Bucuresti.Pentru aceasta se studiaza transmisibilitatea vibratiilor de la sol la piesele din interiorul camerei de intyeractie si, in special, asupra suportului tintei. Cercetarile sunt necesare intrucat experimentele cu raze gama se concentreaza asupra unor tinte care pot fi uneori foarte mici si orice abatere si miscare necontrolata a tintei poate duce la esuarea experimentului.Pe baza rezultatelor obtinute se propune marirea rigiditatii suportului tintei in scopul scaderii transmisibilitatii excitatiilor de la sol la tinta.*

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