Analysis of the natural frequencies of vibrations of the "payload – foam package" system for orbital launch

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Abstract. For launching devices and equipment (payload) into orbit they are usually placed in a foam package made of various polymeric materials. One of the functions of the foam package is to prevent low-frequency vibrations of the payload. In this connection, the problem of determining the natural frequencies of vibrations of the "payload – foam package" system is relevant. These frequencies depend on the physical-mechanical properties and the size of the foam package, the mass and size of the payload. The paper presents the results of an experimental determination of the stiffness characteristics of the foam package materials and a computational analysis of the natural frequencies of the "payload – foam package" system.

1. Introduction

When a payload is delivered into orbit, it experiences intense dynamic loads. The response of the payload to these effects is largely determined by its dynamic properties such as natural frequencies and modes of vibration. For some types of cargo, namely, for electronic devices and equipment, the transportation vibrations can lead to their failure without possible recovery. In this regard, these objects are fixed in the transport position as part of the ship and placed in foam package – a container filled with lightweight elastic foam material containing recesses for dense placement of the payload. The stiffness of the foam packages material is much lower than the stiffness of the payload. At the same time, the low natural frequency of "payload – foam packages" system vibration is regulated: the low natural frequency must be higher than the specified limit value. The prediction of the low natural frequency of the considered system and determination of its possible regulation are crucial scientific and technical tasks to ensure strength of the payload.

The subject of the considered problem is the vibration of a body on an elastic foundation. This subject is characterized by a large number of studies and practical results. A large number of physical and mathematical models describing the behavior of an elastic foundation, should be also noted. Due to their simplicity, the one-parameter and two-parameter models of Winkler and Pasternak are most widely used. Despite the low accuracy of these models, they are widely used since they allow to study quickly the qualitative behavior of the vibrating system [1-9]. The development of these models allows considering certain features of the elastic foundation behavior [10] such as: elastoplastic effects [11]; compression-only deformation [12]; inertial and non-inertial vibration [2]. The formulation of more complex elastic foundation models is carried out using the Levinson-Bharatha and Kerr-Rhines methods [13].

To take into account the physical and technical features of the vibrating system, the heterogeneity of the elastic foundation is described by various options. These are: various laws of stiffness distribution over the elastic foundation space [1, 13]; variable size ratios of the vibrating object and the

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elastic foundation (including cases when the elastic foundation is smaller than the object) [8, 14-16]; variable position of the elastic foundation relating to the object (the location of the elastic foundation is outside [5-7, 9, 14, 17, 18] and inside [9] of the cylindrical shell).

Beams [16], round and rectangular plates and membranes [1-3, 10], cylindrical shells [5-9, 14, 15, 17, 18], including multilayer and functionally graded materials, are typical objects for studying a dynamic behavior. The subject of these studies is the natural frequencies and their dependence on the vibrating system parameters (stiffness and heterogeneity of the elastic foundation, the size ratio of the object and the elastic foundation, the stress-strain model of the object).

2. Problem formulation

A problem formulation is aimed to obtain the generalized results of modal analysis applicable in the range of parameters of the “payload – foam package” vibrating system, which are considered in putting electronic devices and equipment into orbit. From a model point of view, the foam package is an elastic foundation of a special kind. The payload can be described as a homogeneous rectangular parallelepiped mass of 2.0 to 16 kg which is located in the geometric center of the foam package. The foam package also appears to be a homogeneous rectangular parallelepiped with the Young's modulus of the material in the range from 0.05 to 1.30 MPa. As shown in [2], the ratio of the elastic foundation size respecting to the object size higher than 1.5 does not affect the natural frequencies of the vibrating system. The stiffness of the payload material is much higher than the stiffness of the foam package and the size of the foam package is 1.5-4 times greater than the size of the payload. Such values of stiffness and mass are typical for putting electronic devices and equipment into orbit. Thus, the variation intervals of the vibrating system parameters have been defined. The natural frequencies of the vibrating system are mainly determined by the mass of the payload and the stiffness of the foam package.

The aim of the study is to obtain the dependence of the low natural frequency of the payload vibration on the ratio of its mass and the stiffness of the foam package material. To achieve this, it is necessary to perform a series of computational simulations with a numerical (finite element) model of the vibrating system in the considered range of its parameters. To apply the obtained dependencies in assessment of the natural frequencies of real objects, it is vital to carry out an experimental study of the actual stiffness of the foam package material.

3. The numerical model and modal analysis

The geometry of the considered vibrating system is shown in figure 1. The connection between the payload and the foam package was modeled by bonded contacts. The numerical model was meshed by three-dimensional tetrahedral finite elements with three translational degrees of freedom in each node. The boundary conditions were modeled by fixing the six outer edges of the foam package in all directions.

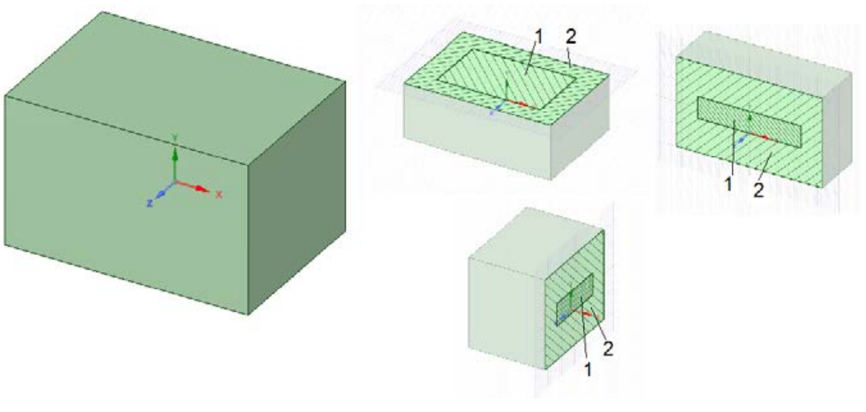


Figure 1. The geometry of the vibrating system: 1 is payload; 2 is foam package with overall dimensions 650 × 450 × 400 mm.

The solution was obtained using the standard linear modal analysis procedure in Ansys. The first mode of vibration shown in figure 2 is the displacement of the payload in the horizontal plane along its long side. The results of series of the calculations are presented in figure 3 as dependences of the natural frequency on the mass of the payload for different Young's modulus of the foam package material.

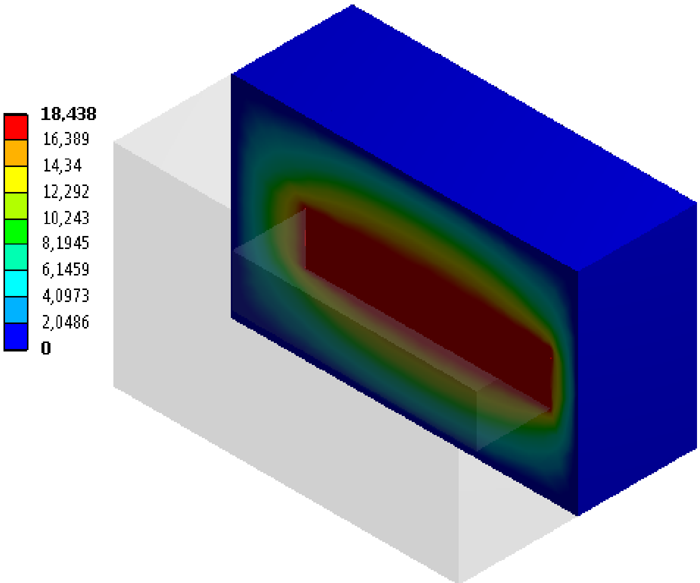


Figure 2. The first mode of vibration (section in vertical plane).

To apply the obtained results in solving applied problems, the series of mechanical tests was performed to determine the Young's modulus of the typical foam package materials. Next, the comparative modal analysis of the electronic device was carried out considering the heterogeneity of its filling with electronic components, mass distribution and stiffness.

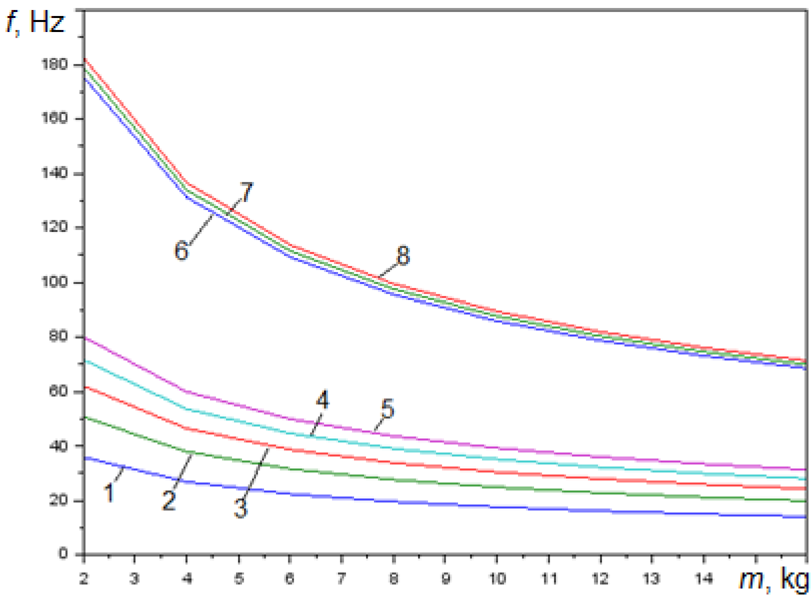


Figure 3. The dependencies of the lowest natural frequency on the mass of the payload for different Young's modulus of the foam package material: 1 is 0.05 MPa; 2 is 0.10 MPa; 3 is 0.15 MPa; 4 is 0,20 MPa; 5 is 0.25 MPa; 6 is 1.20 MPa; 7 is 1.25 MPa; 8 is 1.30 MPa.

4. The mechanical tests of the foam package material

The mechanical tests were carried out on Tinius Olsen 100ST universal testing machine equipped with a non-contact video extensometer. Two materials with different stiffness were tested on compression – polyurethane foam and polyethylene foam. For each material two cubic specimens 90 mm in size were glued together from foam layers of standard thickness as show in figure 4. The specimens were tested in transverse and longitudinal direction. Before testing, the specimens were marked by crosses for non-contact measuring of strains in load direction.

(a) (b)

Figure 4. The specimens of polyurethane foam (a) and polyethylene foam (b).

The specimens were compressed at speed of 10 mm/min, the polyurethane foam by 80 mm and the polyethylene foam by 30 mm. During the tests, the stress-strain diagrams shown in figure 5 were recorded. The stress was calculated as:

$$\sigma = \frac{F}{A_0}, \tag{1}$$

where F is the load, N, and A_0 is the initial cross sectional area, mm^2.

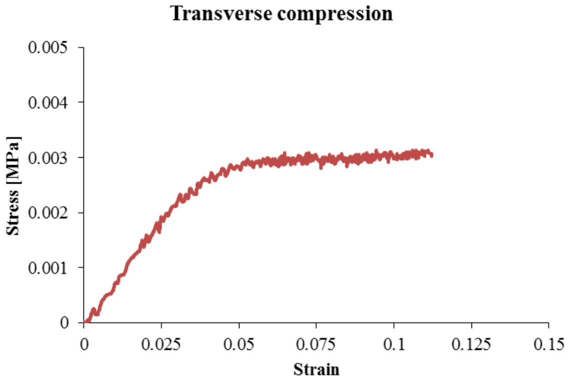
As it is shown on diagrams, the specimens of each material are deformed nonlinearly. There are two distinctive stages of deformation: the first stage with high stiffness and the second stage with low stiffness. The deformation behaviour of the specimens also depends on the load direction. During transverse loading of the foam layers, the specimens are deformed with lower stiffness.

Considering the small deformations of the foam package during transport vibrations, the Young's modulus was determined on the first deformation stage. Based on the diagrams data the Young's modulus was calculated as:

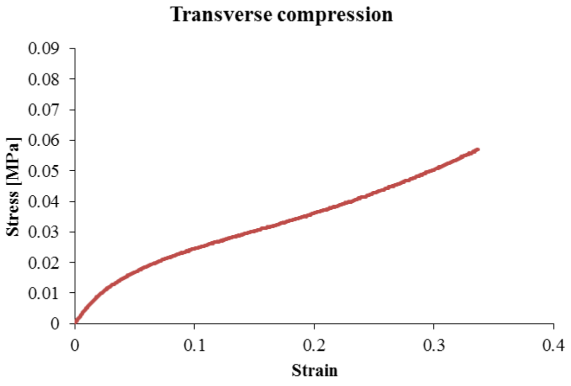
$$E = \frac{\Delta\sigma}{\Delta\varepsilon}, \tag{2}$$

where $\Delta\sigma$ is the change of stress, MPa and $\Delta\varepsilon$ is the corresponding change of strain.

The average value of the Young's modulus of polyurethane foam was 73.78 kPa and polyethylene foam – 1246 kPa. These values characterize the actual stiffness of the foam package material and were used to estimate the natural frequencies of vibration of the payload.



(a)

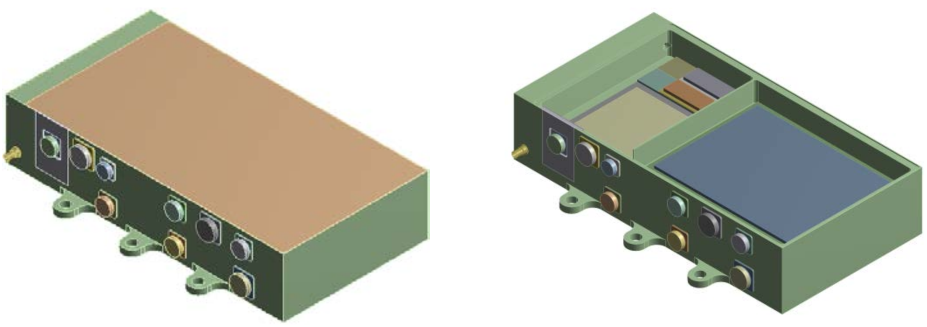


(b)

Figure 5. Stress-strain diagrams for polyurethane foam (a) and polyethylene foam (b) specimens.

5. The vibration analysis of the electronic device in the foam package

The modal analysis of a real device packed in the polyurethane and polyethylene foam was performed by finite element method. The device, shown in figure 6a, consisted of metal body and electronic components. The total mass of the device was 9.7 kg. The device stiffness primarily depends on the body stiffness as the stiffness of the electronic components has negligible contribution. In the finite element model the electronic components were presented as solid bodies of the equivalent mass with low stiffness as shown in figure 6b. The model was meshed by tetrahedral finite elements with 10 nodes and size of 1-5 mm. The materials used in the model had linear and isotropic properties. The material model of the foam package was based on the obtained experimental results.



(a) (b)

Figure 6. The electronic device model: general view (a) and without top cover (b).

The calculated value of the lowest natural frequency of the device model was 21.83 Hz for polyurethane foam package and 89.62 Hz for polyethylene foam package. The lowest natural frequency of the device was also estimated using the dependencies shown in figure 3 which were obtained for solid body payload. The estimated values were 23.23 Hz for polyurethane and 95.45 Hz for polyethylene foam package. The difference in estimates was 6%. This is explained by the inhomogeneous mass distribution in the real electronic device comparing to the homogeneous solid body payload. The inhomogeneous mass distribution affects on the first mode of vibration adding the rotation motion as it is shown in figure 7.

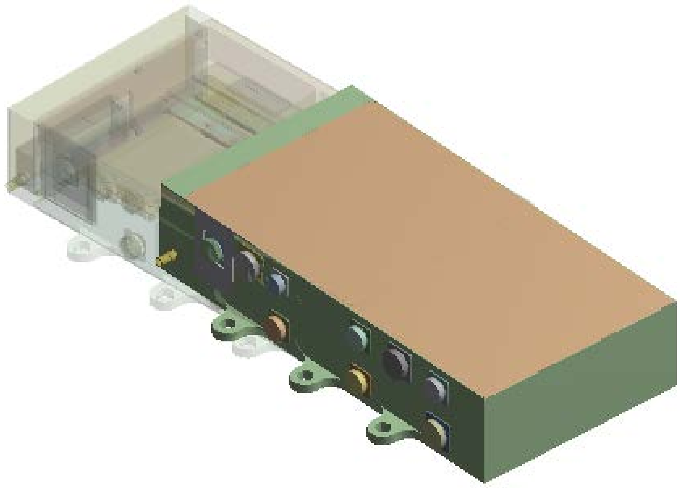


Figure 7. The first mode of vibration of the inhomogeneous electronic device.

6. Conclusion

The modal analysis of a solid deformable body (payload) on an elastic foundation was performed by finite element modeling. The series of calculations allowed building the dependence of a lowest natural frequency of the payload on its mass and the stiffness of the foam package.

The mechanical tests of polyurethane and polyethylene foam package were carried out. The Young's modulus of tested materials was estimated. The experimental results were used in the modal analysis of the real electronic device which launches into orbit in the foam package. The calculated low natural frequency of the device is in a good agreement with the dependencies built previously. Thus, the research results are applicable for modal analysis of various devices and equipment delivered into orbit.

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