DESIGN OF VIBRATION ISOLATING METAMATERIAL WITH QUASI-ZERO EFFECT

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Vibration isolation with high efficiency is very actual for industry. It is important to provide high vibration isolation properties, low natural frequency, low dimensions of isolators and low costs. It is also preferable to obtain vibration isolation of a passive type. A very interesting and promising way of providing high efficiency of vibration isolation is to use quasi-zero stiffness. It means that isolator has special nonlinear force characteristics with very low stiffness at a certain point. But it should be noted there are many problem connected with systems with quasi-zero stiffness like instability, complexity, nonlinearity. Sometimes problems may be connected with high friction, big dimensions and difficult tune-up. A very promising way is to get metamaterial with this effect, i.e. a plate made of elastic material and with complex fine internal structure. This internal structure should provide force characteristics with quasi-zero stiffness at compression of the metamaterial. Width of the metamaterial can be very small. One layer of material can be less than several millimetres. The Paper is devoted to designing of such a metamaterial. Different types of internal structure are presented, that provides vibration isolation in one, two or three dimensions. Detailed analytical analyses, computer modeling and an experimental study have been made. Prototypes of the metamaterial were made with a help of 3D-additive technology. Experimental study shows force characteristics with quasi-zero stiffness. So, this metamaterial can be very effective and compact mean of vibration isolation.

Keywords: metamaterial, quasi-zero stiffness, vibration, vibration isolation

1. Introduction

Vibration is a well-known problem in many fields of industry. Vibration negatively influence on equipment, machines, buildings, foundation and human. Every day more powerful machines and compact are constructed. It leads to concentration of large forces in small volume. In this circumstances problem of vibration isolation may be very important. So, a new ways of protection against vibration should be researched. In this Paper a new trend in materials is offered for vibration isolation. Many scientists suppose that metamaterials will be very widespread in near future. New technologies create great opportunity for 3d manufacturing and application of metamaterials for vibration isolation.

A metamaterial is a composite material whose features are not provided due to properties of constituent material. The features of it are provided by artificial periodic structure. Modify of geometric shapes of internal structure allows to get special properties impossible to be in nature. At this time it is known that with a help of metamaterials it is possible to get negative or magnetic permeability. Such materials are also offered for obtaining special properties connected with acoustics, electrics, optics, electromagnetics, etc.

Modern 3d-additive technologies allow creating materials with complex fine internal structure. So, it is possible to manufacture materials with special vibration isolating properties. Providing special form of internal structure of material allows getting nonlinear force characteristics. Such a system with a flat area on its force characteristic is called systems with quasi-zero stiffness [1]. These systems provide a great advantage compared with conventional vibration isolators - much higher degree of reduction of dynamic forces transmitted due to extra low stiffness at a certain compression [2]. Low stiffness under a certain static load reduces the natural frequency to up to 1 Hz and less that allows isolating a wide range of vibrations with high efficiency [3].

It is already known that quasi-zero stiffness effect can be used for quality vibration isolations. Systems with quasi-zero stiffness are studied by Alabuzhev [1], who analyzed different type of passive systems with quasi-zero stiffness. Carrella studies systems with inclined springs and compressed beams [4, 5, 6]. Quasi-zero stiffness may be also obtained by structures of dome type [2, 3]. The systems can be also achieved by pneumatic active elements as reported in [7] and [8]. "Scissor-like" system with spring for obtaining quasi-zero stiffness is observed by Sun et al [9]. Also systems with quasi-zero stiffness of a passive type are proposed by Le and Maciejewski [10] and Ahn [11]. Note that there is a number of other researches who study this systems. But application of this effect in metamaterial is new and promising.

Due to 3d-additive technologies and idea of metamaterial this mean of vibration isolation can be very thin. One layer of material can be less than several millimeters. Moreover, creating metamaterial with different layers allows getting metamaterial with a set of properties.

This study is devoted to the idea of metamaterial for vibration isolating using quasi-zero effect.

A similar way of obtaining force characteristic with quasi-zero stiffness for vibration isolation by compressed is known by several authors [12, 13] and shows rather good efficiency. Correa and etc [14, 15] also have researches in the area of metamaterial, but their study is devoted to shock absorption. It is also known tunable digital metamaterial for broadband vibration isolation at low frequency [16].

2. Analytical basement of metamaterials for wide broad vibration isolating

Internal structure of the proposed metamaterial is presented on the Figure 1. One cell of the metamaterial is presented on the Figure 2.

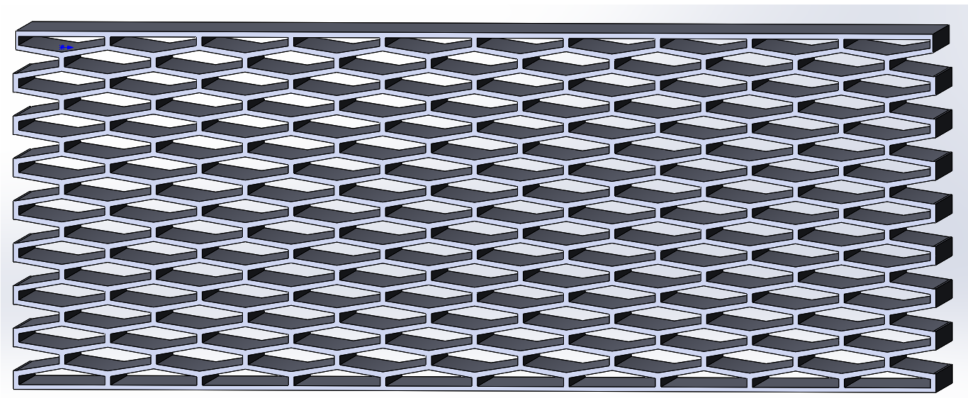

Figure 1: Internal structure of the proposed metamaterial.

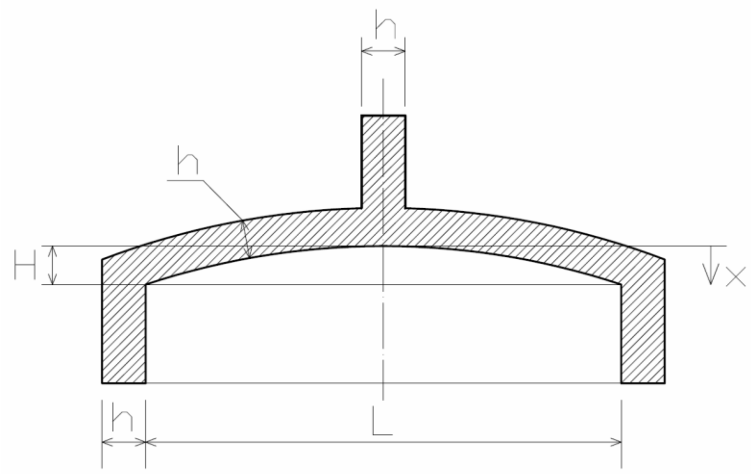

Figure 2: Single cell of the proposed metamaterial.

Next a rough estimate of analytical force characteristic will be done. It is easy to do with a help of potential energy analysis. Potential energy of a cell *W* can be calculated as a superposition of bending and longitudinal compression of the cell. Potential energy of bending equals:

$$W_1 = 12\frac{Ebh^3}{L^3}x^2 .$$

Potential energy of longitudinal compression equals:

$$W_2 = \frac{Ebh}{2L}\Delta^2 .$$

Longitudinal compression can be calculated by several ways. It depends on a shape of deformation of the cell. One way - to consider that cell always has a form of a arc. In this case longitudinal compression equals

$$\Delta = L\left(\frac{\varphi_0}{\sin\varphi_0} - \frac{\varphi}{\sin\varphi}\right).$$

Where angles φ_0 and φ equal

$$\varphi_0 = 2arctg\frac{2H}{L}; \;\; \varphi = 2arctg\frac{2(H-x)}{L}.$$

Other way is to consider that the cell keeps form of a sine function. But evidently, the real form under a load is another and it can be considered by 3d computer modeling. The simplest way is to estimate with a help of sine function. In this case longitudinal compression equals

$$\Delta = \frac{\pi^2 H^2}{4L} - \frac{\pi^2 (H-x)^2}{4L} .$$

After transformations a formula of force characteristics is achieved:

$$F(x) = \frac{\partial}{\partial x}\left(W_1 + W_2\right) = \frac{Ebh}{8L^3}\left[192h^2 x + \pi^4 x(2H-x)(H-x)\right].$$

Force characteristic with quasi-zero stiffness is characterized by a point with minimum stiffness. So, the force characteristic has to have an inflection point.

$$\frac{\partial^2}{\partial x^2}F(x) = 0.$$

Solution of this equation gives an inflection point at x = H. Hence it is an optimum point for the cell from the view point of exploitation.

Stiffness at this point equals

$$\frac{\partial F}{\partial x}(H)=\frac{\partial}{\partial x}(W_1+W_2)=\frac{Ebh}{8L^3}\left[192h^2-H^2\pi^4\right]$$

Stiffness equals zero if the last expression equals zero, so

$$H=\frac{8\sqrt{3}}{\pi^2}h\approx 1.4h.$$

So value of H should be equal or be less than 1.4h.
Load at optimum point equals to

$$F(H)=\frac{24Eh^3Hb}{L^3}.$$

So, with these formulas rough estimation of cell can be done.

3. Computer modelling of the metamaterial

A prototype of metamaterial is offered to be made by 3d printing technology. A common thickness of lines created by wide spread 3d printers equals 0.3 mm. So, consider h = 0.3 mm. The most convenient plastic for this purpose is elastic plastic of type Flex. It has Young's Modulus E = 74 MPa. Other parameters consider b = 10 mm; L = 5 mm; H = 1.4 h = 0.42 mm. Then load at optimum point equals 1.61 N.

Using these parameters a 3d computer model of semi-single cell was calculated with a help of computer program ANSYS. A mesh is presented in the Figure 3. Total number of elements equals 11 thousands. Stress distribution at optimum load is presented on the Figure 4. Maximum stress equals 11.9 MPa, so relative deformation is 16%. It is very good because such a material like Flex Plastic can have deformation up to 100%. So, margin of safety is quite big (more than 6) that is good for vibration isolating materials.

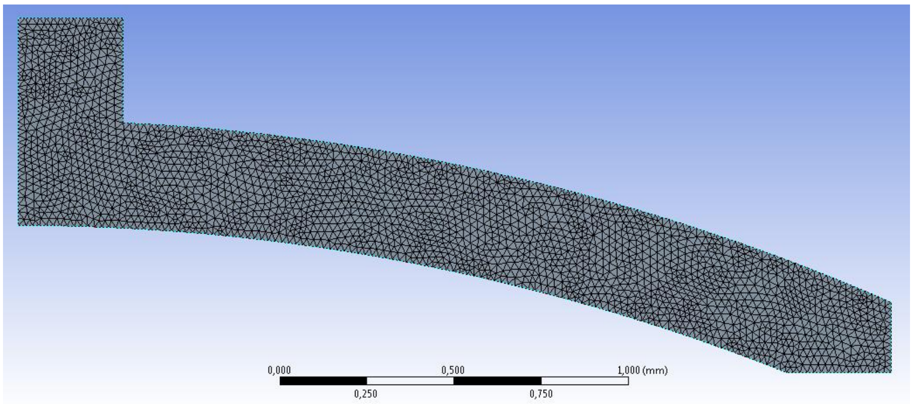

Figure 3: Mesh if the model.

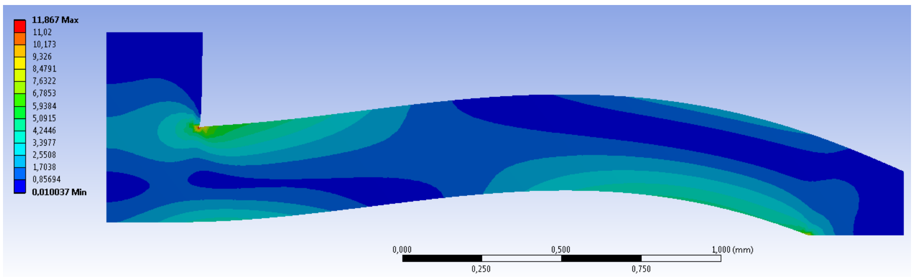

Figure 4: Stress at optimum load.

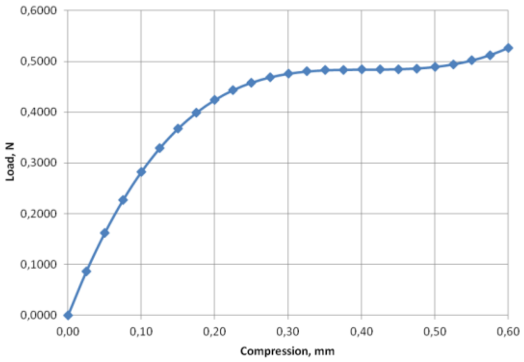

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Figure 5: Force characteristic of a semi-single cell.

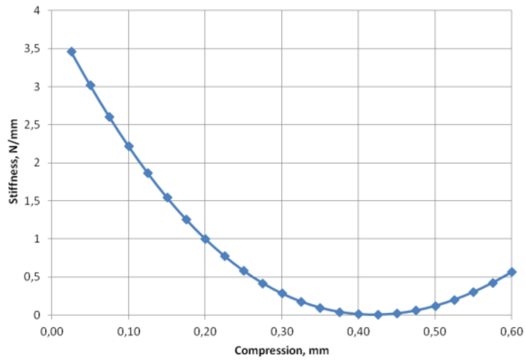

Figure 6: Stiffness of a semi-single cell.

As it follows from Figures 5 and 6 the semi-single cell has quasi-zero stiffness at compression x = 0.42 mm. The minimum stiffness equals almost zero - it is less than 0.01 N/mm (Figure 6). Optimum load for semi-single cell is obtained 0.7 N, so single cell has an optimum load 1.4 N. So, we see the results of analytical assessment and computer modelling are similar. So, very promising results are obtained. Optimum load of a single cell is 1.4 N and it is obtained by dimensions 5 mm x 10 mm. Hence optimum load the whole metamaterial is 0.028 N/mm^2, or 2.8 ton per m^2. The value is enough for non-heavy industrial. These results allow assessing efficiency of the proposed metamaterial. Natural frequency is calculated by the formula

$$\upsilon = \frac{1}{2\pi}\sqrt{\frac{k}{m}} = 0.3\ Hz.$$

This as an excellent value of natural frequency that provides quality vibration isolation in a wide range of frequencies. But the real parameters can be obtained only by experimental study.

4. Prototyping

Real models were made by 3d printer Picaso Designer (Figure 7). Flex Plastic with Young's Modulus 74 MPa was used. Thickness of lines equals 0.3 mm.

Figure 7: Real models of metamaterial.

The prototype has 8 and 9 cell per layer. Force characteristic of a prototype was measured and it is presented on the Figure 8.

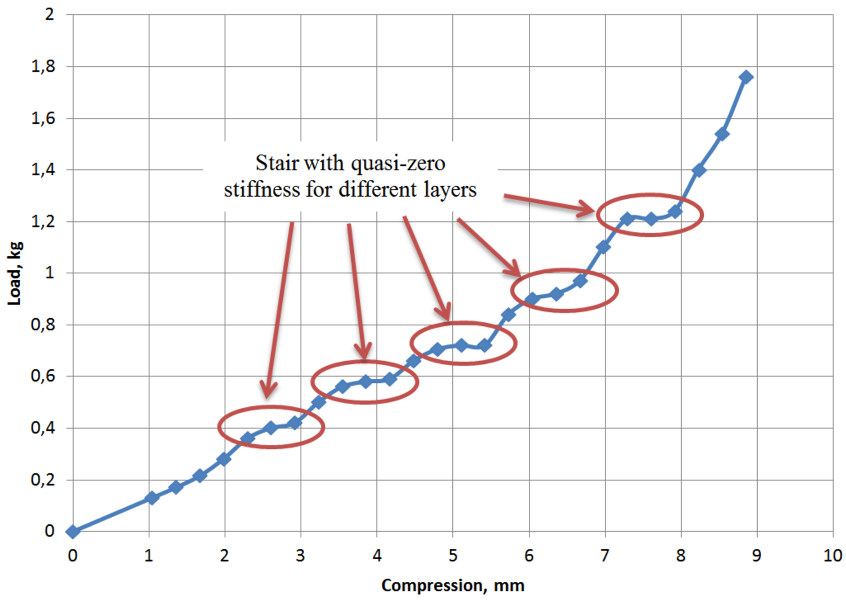

Figure 8: Real models of metamaterial.

As it follows form the Figure 8 the metamaterial really has areas with quasi-zero stiffness. The force characteristic has different steps, so quasi-zero stiffness is presented at a various load. The load of each step is a multiple of approximately 0.15 N, i.e. a value of an optimum load of a single cell as it was calculated before. The fact than the steps coincides not only to the layer with 8 or 9 cells means that several cell doesn't work properly. Observation has shown that several cells are broken (bad adhesion of printing plastic). Solving of this problem is a task for future study.

5. Conclusions

In this study design of a new metamaterial for vibration isolation is presented. The idea is to create an internal structure that provides quasi-zero stiffness at compression. Analytical and computer analysis have shown that it has very low stiffness and hence extra low natural frequency. These results are a very promising for efficient and wide broad vibration isolation.

A prototype is made by 3d-additive technologies. A force characteristic is obtained. It has steps with quasi-zero stiffness that proves the idea of vibration isolating metamaterial. It is also achieved that a complex force characteristic can be obtained, i.e. the metamaterial can have simultaneously different optimum loads.

REFERENCES

1 Alabuzhev, P.A., Gritchin, L., Kim, L., Migirenk,o G., Chon, V. and Stepanov, P., *Vibration Protecting and Measuring Systems with Quasi-Zero Stiffness*, Hemisphere Publishing, New York, (1989).

2 Valeev, A.R. and Kharisov, Sh. A. Application of Vibration Isolators with a Low Stiffness for the Strongly Vibrating Equipment, Procedia Engineering, *Proceedings of the 2nd International Conference on Industrial Engineering (ICIE-2016)*, **150**, (641-646), 2016.

3 Valeev, A.R., Zotov, A.N., Kharisov, Sh. A.. Designing of compact low frequency vibration isolator with quasi-zero stiffness. *Journal of low frequency noise, vibration and active control*. **34** (4), 459-474, (2015).

4 Carrella, A. and Friswell, M.I.. A passive vibration isolator incorporating a composite bistable plate. *Proceedings of 6th European Nonlinear Dynamics Conference*, Saint Petersburg (Russia), 30 June- 4 July 2008.

5 Carrella, A., Brennan, M., and Waters, T.P. Static analysis for a passive vibration isolator with quasi-zero stiffness characteristic. *Journal of Sound and Vibration* (2007), **301** (3-5), 678-689.

6 Carrella, A., Brennan, M., and Waters, T.P. Optimization of a quasi-zero-stiffness isolator. Journal of *Mechanical Science and Technology* (2007), **21**, 946-949.

7 Sun, X., Xu J., Jing, X. and Cheng, L. Beneficial performance of a quasi-zero-stiffness vibration isolator with time-delayed active control. *International Journal of Mechanical Sciences* (2014), **82**, 32–40.

8 Le, T.D. and Ahn, K.K. Fuzzy sliding mode controller of a pneumatic active isolating system using negative stiffness structure. *Journal of Mechanical Science and Technology* (2012), **26** (12), 3873-3884.

9 Sun, X., Xu, J., Jing, X. and Cheng, L. Beneficial performance of a quasi-zero-stiffness vibration isolator with time-delayed active control, *International Journal of Mechanical Sciences* (2014), **82**, 32–40.

10 Maciejewski, I., Meyer, L. and Krzyzynski, T. Modelling and multi-criteria optimization of passive seat suspension vibroisolating properties. *Journal of Sound and Vibration* (2009), **324**, 520–538.

11 Le, T.D. and Ahn, K.K. A vibration isolation system in low frequency excitation region using negative stiffness structure for vehicle seat. *Journal of Sound and Vibration* (2011), **330**, 6311–6335.

12 Carrella, A. Passive vibration isolators with high-static-low-dynamic-stiffness, Ph.D. Thesis, University of Southampton, UK, (2008).

13 Valeev, A.R., Zotov, A.N. and Tikhonov, A.Yu. Vibration isolating shafts suspension with quasi-zero stiffness, *Problems of gathering, treatment and transportation of oil and oil products*, **3**, 68-77, (2010).

14 Correa, D.M., Seepersad, C.C. and Haberman, M.R. Mechanical design of negative stiffness honeycomb materials. *Integrating Materials and Manufacturing Innovation* (2015) 4:10

15 Correa, D.M., Klatt, T.D., Cortes, S.A., Haberman, M.R., Kovar, D., and Seepersad, C.C. Negative Stiffness Honeycombs for Recoverable Shock Isolation. *Rapid Prototyping Journal*, (2015)

16 Wang, Z., Zhang, Q., Zhang, K. and Hu, G. Tunable digital metamaterial for broadband vibration isolation at low frequency. *Advanced materials*, (2016)