VIBRATION ISOLATING MATERIAL WITH INTERNAL STRUCTURE PROVIDING QUASI-ZERO STIFFNESS

Valeev Anvar

Ufa State Petroleum Technological University, Ufa, Russian Federation

email: anv-v@yandex.ru

Vibration isolation is frequently met problem in many industries. Modern equipment often requires high-quality vibration isolation. However, a current trend for compactness of machines and equipment leads to necessity of compact and effective vibration isolators. One of the most effective way to provide high parameters of vibration isolators is application of quasi-zero stiffness effect, i.e. to get low dynamic stiffness at a high load (or at high static stiffness). But such vibration isolators have some problems or disadvantage. The main disadvantage is a high sensitivity in manufacture or tuning. Vibration isolators with quasi-zero stiffness require either a number of elements or a special form. In this study for making the vibration isolators with quasi-zero stiffness more effective, simple and handy, it is offered to manufacture the isolator like a solid material. But this material consists of two components and contains a defined structure providing quasi-stiffness stiffness effect. General view like a mat provides handy application and exploitation of the presented material. Combination of quasi-zero effect and simplicity of isolating mats makes the offered material very perspective. In this study internal structure of such vibration isolating material with quasi-zero stiffness is shown. Analytical, computer and experimental studies have been made, that shows great opportunity of application in different fields.

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

1. Introduction

Nowadays machines and equipment are always being improved. It's power increases, but dimensions are usually decrease. So, a great power can be concentrated in a small volume, that can cause problems with vibration. Prolonged exposure of vibration harmfully affects on equipments, construction and humans.

One of the most perspective ways to provide high quality vibration isolation is to use vibration isolators and vibration isolating material with non-linear characteristics. A so called quasi-zero effect can be used for this purpose.

Vibration isolators with quasi-zero stiffness present a very promising trend in mechanical engineering. They can be applied in various fields, like industrial machines and equipment, ship engines, heavy-duty vehicles, hand-held machines, precision equipment, aerospace equipment, etc. Vibration isolators with quasi-zero stiffness characterized by high static load and low dynamic stiffness, that allows isolating a wide range of vibration with high efficiency.

Firstly study of vibration isolators with quasi-zero stiffness began by Alabuzhev [1]. Carella is also known due to analysis of quasi-zero stiffness obtained by two inclined springs [2] or two stable
states (bistable plate) [3, 4, 5]. "Scissor-like" system with spring for obtaining quasi-zero stiffness is observed by Sun et al [6]. Also systems with quasi-zero stiffness of a passive type are proposed by Le and Ahn [7] and Maciejewski [8]. Origami-based foldable cylinders with torsional buckling patterns also may provide quasi-zero stiffness [9]. It is also known that it is possible to obtain quasi-zero stiffness with cam-roller-spring mechanisms [10].

Different vibration isolating systems with quasi-zero stiffness can be also made due to active or semi-active methods. Various methods and equipment were presented by Choi et al [11, 12], Gan et al [13], Kawana and Shimogo [14], Robertson et al [15], Donghong Ning et al [16], Zheng et al [17] and other scientists.

One of the ways to manufacture vibration isolators is to use polymeric and composite material. It's very good from economical point of view, there is no need of complex and prolong technical operations. But application of use polymeric and composite materials is connected with such a feature as relaxation/creep of a material.

Modern materials and new achievements in 3D manufacturing creates opportunities in creating complex internal structure in materials. This way may be used for obtaining special structure in elastic materials, i.e. for improved vibration isolation [18, 19]. Creating special shape of the internal structure of the material provides a non-linear force characteristic, particularly force characteristic with quasi-zero stiffness. Such a material with complex internal structure may have great advantages in vibration isolating, but also disadvantages, such as relaxation, creep, tuning difficulties.

2. Creep and relaxation in materials with quasi-zero stiffness

Due to creep polymeric and composite materials tends to further deformation under a load. It can occur due to long-term exposure to high levels of stress that are still below the yield strength of the material. The rate of creep is a function of many parameters, such as material's properties, exposure time, exposure temperature, applied structural load, etc. On the other hand, stress relaxation is the decrease in stress in response to the same amount of strain generated in the structure [20].

In vibration isolators with quasi-zero stiffness it is very important to provide certain deformation of isolators and to provide a certain load for obtaining quasi-zero effect. If the load or deformation is not optimal, hence quasi-zero effect would be low. Hence creep and stress relaxation provide very negative effect in systems with quasi-zero stiffness. So studying of it is very import for development of polymeric and composite vibration isolators with quasi-zero stiffness effect.

According to Maxwell model of the Stand Linear Solid stress relaxation can be calculated as [21]:

\[
\sigma(t) = \varepsilon_0 \left(k_e + k_1 \exp\left(-\frac{t}{\tau}\right)\right)
\]

(1)

Where \( t \) – time; \( \varepsilon_0 \) – nominal compression; \( k_e \) and \( k_1 \) – nominal stiffness; \( \tau \) – time parameter.

For experimental analysis of stress relation the following isolators [22, 23] were used (Fig. 1). Experimental installation is presented on the Fig. 2.

Figure 1: Vibration isolators with quasi-zero stiffness
Figure 2: Experimental installation for stress relation analysis of isolators with quasi-zero stiffness

Experimental installation consists of mechanical press, electronic module with strain gauge. Electronic module is connected to computer via USB cable. It transfers values of load at strain gauge to computer every 0.2 second. Data was collecting for 2 hours (part of the data is presented on the Fig. 3).

Figure 3: Experimental data of relaxation analysis

According to experimental data stress relaxation can be estimated as (dimension of load in grams; time in seconds):

$$\sigma(t) = 12962 + 2087 \cdot \exp(-0.022858 \cdot t).$$

So, extrapolating this data according Maxwell model load tends to 12.962 kg. However, initial load equals 16.582 kg, i.e. load decrease 21.8%. As systems are very sensitive to tuning it is very import to take into account relaxation effect, hence to use appropriate material with low relaxation properties.
3. Design of material with quasi-zero stiffness

It is known that lead, brass, bronze, aluminum and some other non-ferrous metals and alloys, as well as plastics, polymer-based composites, fiberglass, etc. has relaxation and creep properties. So, in order to provide stable parameters of vibration isolators and materials with quasi-zero stiffness appropriate material should be used, for example spring steels or high durable elastic polymers.

For obtain high and stable properties of vibration isolating material with internal structure providing quasi-zero stiffness an improved design is offered (Fig. 4).

![Figure 4: Vibration isolating material with internal structure providing quasi-zero stiffness](image)

Presented vibration isolating material consists of internal layer in pre-buckling condition. Intermediate space between elements of this layer is filled by air or soft material. Soft material may be a soft rubber, silicone, soft damping material. So, internal with quasi-zero stiffness has low natural frequency and isolates low frequency vibration. Elastic layer isolates high frequency vibration and noise.

4. Mathematical modelling of two-component material with quasi-zero stiffness

Mathematical modelling of proposed material with quasi-zero stiffness is presented below. On the Fig. 5 a sketch of single cell is presented.

![Figure 5: Single cell of the material](image)

\[ E_1 \text{- Young's modulus of air or soft elastic materials; } E_2 \text{- Young's modulus of the hard elastic materials; } L, S, t_i, h_i, t, t_0, x_1, x_2 \text{- geometrical parameters} \]
Energy method for mathematical analysis of the material is used. By this method force characteristic can be assessed. Deformation of the cell is taken as a deformation of the following elements: compression of the zone I, compression of the zone II, longitudinal compression of the inclined wall, bending of the inclined wall.

Total energy equals:

$$W = 2W_{n1} + 2W_{n2} + W_c + W_b.$$  \hspace{1cm} (3)

Here $W_{n1}$ - potential energy of compression of the zone I; $W_{n2}$ - potential energy of compression of the zone II; $W_c$ - potential energy of compression of the inclined wall; $W_b$ - potential energy of bending of the inclined wall. This variable can be assessed as:

Energy of compression of the zone I equals:

$$W_{n1} = \frac{E_1 b(L + t)}{\frac{1}{2}(h_{t2} + h_{t1})} \cdot \left( \frac{\Delta x_1 + \Delta x_2}{h_{t1} + t} \right)^2.$$  \hspace{1cm} (4)

Energy of compression of the zone II equals:

$$W_{n2} = \frac{E_2 b t}{h_{t2}} \cdot \Delta x_2^2.$$  \hspace{1cm} (5)

Energy of compression of the inclined wall equals:

$$W_c = \frac{E_1 b t}{\sqrt{L^2 + S^2}} \cdot \Delta L^2.$$  \hspace{1cm} (6)

Energy of bending of the inclined wall equals:

$$W_b = \frac{1}{8 \left( \frac{E_2 b t^3}{\sqrt{L^2 + S^2}} \right)} \cdot \Delta y^2.$$  \hspace{1cm} (7)

Here $E_1$ - Young's modulus of the soft elastic materials; $E_2$ - Young's modulus of the hard elastic materials; $\Delta x_1$ - decrease of the value $x_1$ under load; $\Delta x_2$ - decrease of the value $x_2$ under load; $b$ - thickness of the material; $\Delta L$ - decrease of the value $L$ under load; $\Delta y$ - decrease of the value $S$ under load; $x$ - compression of the material.

Taking into account relationships between geometrical parameters a formula for load relative to compression can be derived. Note, for obtaining quasi-zero effect stiffness at a certain compression equals zero. The lowest stiffness reaches at $x=S$. Mathematical analysis this have been done. Particularly, it is obtain that the following parameters provides quasi-zero effect:

$$\frac{E_1}{E_2} = 0.01; \quad \frac{b}{L} = 1; \quad \frac{h_{t1}}{L} = 0.1; \quad \frac{t}{L} = 0.1; \quad \frac{t}{L} = 0.4; \quad \frac{S}{L} = 0.61;$$  \hspace{1cm} (8)

For these parameters optimal load equals

$$\frac{F}{b L E_2} = 0.042.$$  \hspace{1cm} (9)

So, if we define parameters $E_2=10$ MPa; $E_1=0.1$ MPa; $L=10$ mm; $b=10$ mm; $h_{t1}=5$ mm; $t=5$ mm; $t=4$ mm; $S=6.1$ mm optimal load equals 8 N or 8154 kg per 1 m².

5. Computer analysis of two-component material with quasi-zero stiffness

Computer analysis via Ansys have been done in order to check analytical formulas derived in the previous section. For this purpose Mechanical Static Structural Module with option “large deflections” have been applied. General view of the computer model is presented on the Fig. 6. Static force characteristic obtained by Ansys is presented on the Fig. 7.
As a result, optimal load equals 8.5 N; compression of the material at this load equals 5.5 mm. As we can see, analytical analysis coincides with computer one.

6. Conclusions

A material with internal structure providing quasi-zero stiffness is presented in this Paper. One of the significant problems of isolators with quasi-zero stiffness is stability of parameters due to relaxation/creep effect. Relaxation makes the isolator untuned and decreases vibration isolating parameters. So, very careful designing and material choosing should be done.

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