

Investigation into Working Mechanism of Molecular Spring Isolator

M.C. Yu, Q. Chen and X. Gao

Abstract — This paper initiates a new passive vibration isolation technology --- *molecular spring isolator*. *Molecular spring isolator* consists of water and hydrophobic zeolites as working medium. When it is subjected to vibration, water constantly intrudes into and extrudes from hydrophobic pores of zeolites so that energy is stored, released and dissipated. The molecular spring possesses a piecewise nonlinear stiffness, which exhibits high static and low dynamic stiffness characteristics. Hence, the molecular spring isolator is suitable for heavy equipment vibration isolation with super-low natural frequency.

To obtain the dynamic property of molecular spring isolator, mechanic model of water column intruding into a hydrophobic pore is established with force equilibrium method. Then the process of water molecules flowing into large numbers of hydrophobic pores is explored under the assumption that the contact angle distribution is Gaussian and the aperture is evenly distributed on the surface of a zeolite particle. Last, the measured mechanic property was obtained from the quasi-static experiment, which shows a good agreement with the predicted one.

Index Terms — molecular spring, hydrophobic zeolites, piecewise stiffness, vibration isolation, super-low isolation frequencies

I. INTRODUCTION

PASSIVE vibration isolators have been widely used due to their advantage of structural simplicity and high reliability. Although there are a few passive vibration isolators such as helical spring isolator, rubber isolator, air spring, wire-rope vibration isolator, metal rubber isolator and solid and liquid mixture (SALiM) isolator [1]–[2] etc., the performances of those vibration isolators are not entirely satisfactory for heavy equipment vibration isolation. It is well known that heavy loading capacity requires high static stiffness, which leads to high isolation frequency which is undesired. To overcome the contradictory between the heavy loading capacity and low isolation frequency, new vibration isolation technologies are still desired for vibration control of engineering systems.

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In this work, an innovation of a new passive vibration isolation technology is introduced. The *molecular spring* vibration isolator is illustrated in Fig. 1, which consists of hydraulic cylinder filled with water and zeolites particles. In general, nanoporous materials, such as zeolites, are usually utilized in chemical field. Nevertheless, recent studies found unique mechanic properties of nanoporous hydrophobic solids[3]. Water molecules will intrude into pores of hydrophobic zeolites under certain hydraulic pressure. During this process, mechanical energy will transform into interfacial energy. Extrusion arises automatically with hydraulic pressure decreasing [4]–[9] and at the same time interfacial energy turns back to mechanical energy. Therefore, during the cycle of compressing and decompressing the mixture of water and hydrophobic zeolites, energy is stored, released and partially dissipated. As it works like a spring, the mixture of water and hydrophobic zeolites is named as *molecular spring*.

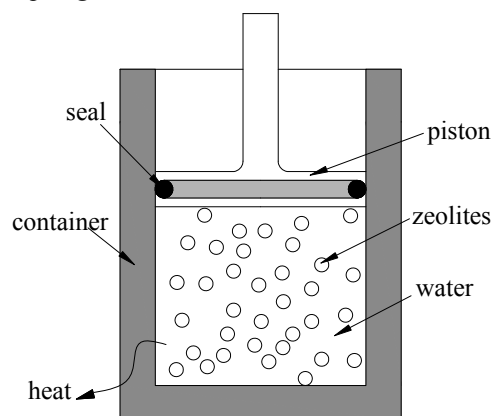


Fig. 1. Schematic view of molecular spring isolator

Zeolites are microporous crystalline materials with an inorganic, three dimensional host structure comprised of fully linked, corner-sharing tetrahedron. Different types of zeolites may possess different pores such as 1D, 2D, 3D or cage-like channels. Due to large numbers of pores, zeolites have large specific surface area and high porosity. Hence, zeolites are usually utilized as sorbent and catalyzer. Silicalite-1, as shown in Fig. 2, is MFI type zeosil which is first synthesized in 1978. The silicalite-1 framework contains interconnected channels of pores of two types: straight channels which run in the direction of y-axis and zigzag channels parallel to the xz plane. As silicalite-1 exhibits the character of high hydrophobicity, good thermal stability, water stability and chemical stability, it makes an excellent medium for molecular spring. Water is polar liquid with high surface tension, and the diameter of water molecule is smaller than 0.3 nm. Consequently, water molecules can penetrate into very small pores.



Fig. 2. Zeolites

Force equilibrium of water column in a pore is utilized to establish the mechanics model of water intruding into a single hydrophobic pore. A commercial silicalite-1 is adopted to compose a *molecular spring isolator*. The stiffness of the isolator is tested experimentally to validate the theoretical calculation.

II. THEORETICAL CALCULATION OF FORCE-DISPLACEMENT RELATION

The purpose of this section is to establish a mechanic model of *molecular spring*. Water is forced into hydrophobic micropores (whose diameter is less than 2nm) and expelled from micropores periodically, which is the working mechanism of molecular spring.

A. Water intrudes into single hydrophobic pore

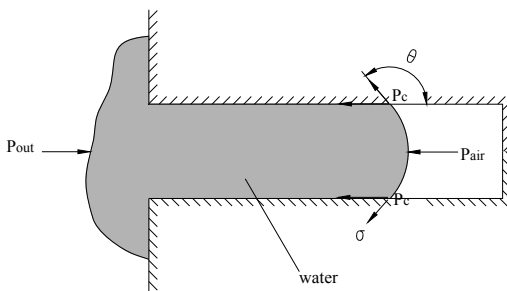


Fig. 3. Laplace capillary pressure

Fig. 3 illustrates the force equilibrium of water column in a hydrophobic pore. Under outer pressure P_{out} , water will overcome the capillary pressure P_c and inside air pressure P_{air} , and thus intrudes into the hydrophobic pore. In Fig. 2, contact angle θ reflects the scale of hydrophobicity. For water and hydrophobic solid, θ is over 90 degrees. Denote the radius of the pore as r and surface tension of water as σ_L , one can get the noted Laplace-Washburn equation which gives the capillary pressure:

$$P_c = -2\sigma_L \cos\theta / r \quad (1)$$

As the pore size is nanoscale, P_{air} is ignorable. Therefore,

$$P_{out} = P_c \quad (2)$$

That means, when *molecular spring* is compressed, water will not intrude due to the hydrophobicity of zeolites until pressure reaches level P_c . Whereas, for a single pore, once arriving at the pressure, water flows into the pore space till saturation. It is worthy to mention that for nanoscale pores, it is necessary to consider the influence of circular interface [10] when capillary pressure is calculated using (1).

B. Water intrudes into a large number of hydrophobic pores

Practically, water intrudes into a large number of pores when *molecular spring*, the mixture of water and hydrophobic zeolites, is compressed. Further more, the aperture and hydrophobicity scale of the pores are different from each other. There are three compressing phases when the volume of the water in *molecular spring* decreases with hydraulic pressure rising. And it is necessary to considered water compressibility. Firstly, the pressure is insufficient and no water molecules penetrate into hydrophobics pores. Under this condition, compressibility of water contributes all the volume decrement of *molecular spring* mixture. As a result, the volume of the mixture shrinks slowly with pressure increasing. In the second phase, hydraulic pressure is high enough to overcome P_c so intrusion of water molecules takes place. In this period, water flows into the hydrophobic pores almost freely with pressure increasing gradually. Therefore, slight increase of pressure leads to visible decrease of *molecular spring*'s volume. *Molecular spring* is quite soft in this phase. Before proceeding to the next phase, all pores have been saturated with water. Consequently, no more water intrusion occurs in the last phase so that water compressibility contributes to all the volume decreasing again.

According to (1), the proceeding of water intruding into hydrophobic pores is affected by pore diameter and the contact angle. When *molecular spring* mixture is pressed, water firstly intrudes into pores which have biggest apertures and smallest contact angles. And then water flows into smaller apertures with larger contact angles gradually till all pores are saturated.

Considering the characteristics of zeolites' pores and the defects of commercial zeolites, it's reasonable to assume that the aperture of zeolites is uniformly distributed in a certain range. And at the same time, the contact angle is assumed to be Gaussian distribution which belongs to $\theta \sim N(\mu, \eta^2)$. θ ranges from a certain value to π .

Sign exterior hydraulic pressure as P . r_{min} and r_{max} are the minimum and the maximum radii of pores. The minimum contact angle of pores is denoted as θ_{min} . The mass of zeolites is m and pore volume of every unit mass of zeolites is V_{pore} . V_{water} denotes the volume of water. Compression ratio of pure water is $\beta(P)$.

Furthermore, pores' volume distributing function against aperture is:

$$V_0(r) = \frac{r_{max} - r}{r_{max} - r_{min}} \cdot m \cdot V_{pore} \quad (3)$$

And probability density function of contact angles is signed as

$$f_0(\theta) = \frac{f(\theta)}{F(\pi) - F(\theta_{\min})} \quad (4)$$

where:

$$f(\theta) = \frac{1}{\sqrt{2\pi}\vartheta} e^{-\frac{(\theta-\mu)^2}{2\vartheta^2}} \quad (5)$$

$$F(\theta) = \int_{-\infty}^{\theta} f(t)dt = \frac{1}{\sqrt{2\pi}\eta} \int_{-\infty}^{\theta} e^{-\frac{(t-\mu)^2}{2\eta^2}} dt \quad (6)$$

To simplify the formulae, define

$$V_a = \frac{r_{\max} - \left(\frac{-2\sigma \cos \theta}{P}\right)}{r_{\max} - r_{\min}} \cdot m \cdot V_{pore} \quad (7)$$

$$V_b = \frac{\frac{2\sigma}{P} - r_{\min}}{r_{\max} - r_{\min}} \cdot m \cdot V_{pore} \quad (8)$$

$$V(P) = \begin{cases} V_{water}\beta(P), & \left(P < \frac{2\sigma \cos \theta_{\min}}{r_{\max}}\right) \quad (a) \\ V_{water}\beta(P) + \int_{\theta_{\min}}^{\arccos\left(\frac{-Pr_{\max}}{2\sigma}\right)} V_a f_0(\theta) d\theta, & \left(\frac{2\sigma \cos \theta_{\min}}{r_{\max}} \leq P < \frac{2\sigma \cos \theta_{\min}}{r_{\min}}\right) \quad (b) \\ V_{water}\beta(P) + \int_{\theta_{\min}}^{\arccos\left(\frac{-Pr_{\min}}{2\sigma}\right)} m V_{pore} f_0(\theta) d\theta + \\ \int_{\arccos\left(\frac{-Pr_{\max}}{2\sigma}\right)}^{\arccos\left(\frac{-Pr_{\min}}{2\sigma}\right)} V_a f_0(\theta) d\theta, & \left(\frac{2\sigma \cos \theta_{\min}}{r_{\max}} \leq P < \frac{2\sigma}{r_{\max}}\right) \quad (c) \\ V_{water}\beta(P) + V_0 \left(\frac{2\sigma}{P}\right) + \int_{\theta_{\min}}^{\arccos\left(\frac{-Pr_{\min}}{2\sigma}\right)} V_b f_0(\theta) d\theta + \\ \int_{\arccos\left(\frac{-Pr_{\min}}{2\sigma}\right)}^{\pi} V_b f_0(\theta) d\theta, & \left(\frac{2\sigma}{r_{\max}} \leq P < \frac{2\sigma}{r_{\min}}\right) \quad (d) \\ V_{water}\beta(P) + m V_{pore}, & \left(P \geq \frac{2\sigma}{r_{\max}}\right) \quad (e) \end{cases} \quad (9)$$

As mentioned earlier, there are three phases when *molecular spring* is compressed. During the first phase, compressibility of water contributes all the volume decrement of molecular spring. The volume decrement $V(P)$ can be evaluated by (9a). The second phase is water intrusion phase which consists of three procedures. First intrusion procedure, hydrophobic channels with big apertures and small contact angles are available to water molecules. As pressure keeps rising, it comes to the second intrusion procedure. Pores with large contact angles are penetrable. And Pores whose contact angle are smaller than $\arccos(Pr_{\min}/(2\sigma))$ are saturated. Continue to increase the pressure on the mixture, it reaches the third intrusion procedure. Pores whose radii are larger than $2\sigma/P$ have reached saturation. The pores whose radii are smaller

than $2\sigma/P$ but contact angles are smaller than $\arccos(Pr_{\min}/(2\sigma))$ are also saturated at the same time. $V(P)$ of these three procedures are shown in (9b), (9c), and (9d). Lastly, it comes to the third compressing phase with all pores filled with water. Apparently, as given in equation (9e), $V(P)$ consists of condensation volume of pure water and volume of zeolites' pores.

So we finally get the relationship of $V(P)$ and exterior hydraulic pressure in (9). Decompression process is right the inverse procedure of compression. So there is no excrement description in this paper.

(9)

III. QUASI-STATIC EXPERIMENT

An experiment was arranged to validate the estimated stiffness properties of *molecular spring*. A *molecular spring* isolator of cylinder-piston structure was designed. Water and hydrophobic zeolites were filled in the cylinder and piston was utilized to apply the hydraulic pressure. The quasi-static test was carried out using a universal testing machine (Fig. 4).



Fig. 4. Test rig

The experimental results are shown in Fig. 5. Clearly, the stiffness of *molecular spring* mixture is piecewise nonlinear stiffness with high-low-high three parts, which exhibits high static and low dynamic characteristic. We name the three parts of nonlinear stiffness as static stiffness, dynamic stiffness and stopping stiffness. The loading procedure starts with first high stiffness loading part. Then it comes across soft dynamic stiffness working part when force comes to 6.0 KN. At about 9.0 KN, the curve turns to high stiffness stopping part.

It can be seen in Fig. 5 that stiffness of stopping part is quite close to that of loading part, which parallels stiffness of compressing pure water. Obviously, stiffness of working part is much lower than that of loading part and stopping part. That is because the intrusion of water molecules occurs during working part.

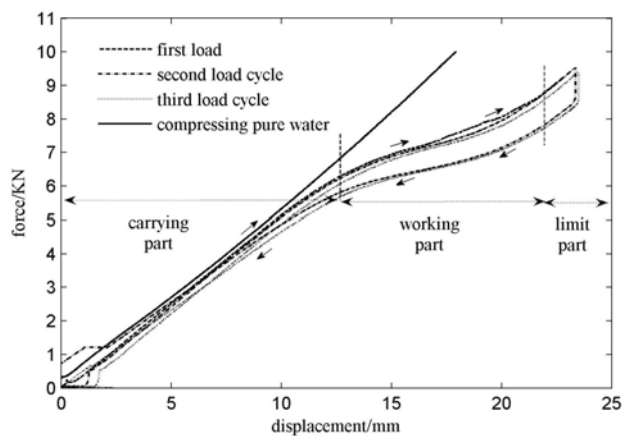


Fig. 5. Quasi-static experimental data

At the beginning of decompressing process, force suddenly changes and a jump phenomenon occurs. The drop is caused by the gaps in the machine when the force changes direction.

Manifestly, the experimental force-displacement curve is very close to the theoretical one as given in Fig. 6.

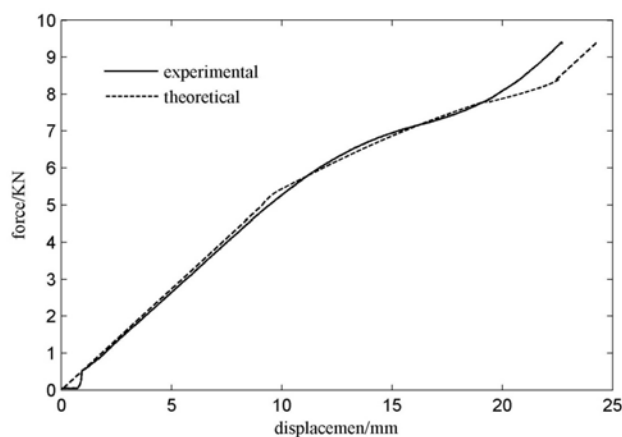


Fig. 6 Experimental result and theoretical result

To take advantage of the unique stiffness properties of *molecular spring*, appropriate mass should be loaded. With the weight of the mass, the *molecular spring* isolator stays on in working part when vibrating. High loading stiffness guarantees high carrying capacity, the low dynamic stiffness makes the super-low isolation frequency possible, and the high stopping stiffness supplies a good protection constraint under impact. Therefore, *molecular spring* isolator can support a heavy load while having super-low dynamic stiffness.

IV. CONCLUSION

This paper introduces a new vibration isolation technology, *molecular spring* isolator which is particularly suitable for heavy equipment vibration isolation and shock absorption. The stiffness of *molecular spring* is a piecewise nonlinear stiffness, which provides high-static-low-dynamic stiffness property which is highly demanded in vibration control area. It is anticipated that thanks to its exceptional advantages, the *molecular spring* vibration isolation technology could find promising engineering application to heavy equipment

vibration isolation as it can support a heavy load while having super-low dynamic stiffness or isolation frequency.

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