Performance Characteristics of SALiM Isolator

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***Abstract* — This paper describes a type of isolator which is based on Solid And Liquid Mixture (SALiM) for vibration isolation and shock absorbing. The nonlinear force-displacement relation of the isolator is established. Using the precise integration method, the primary responses in time domain are evaluated to study the isolator's property.**

***Index terms* — Solid and Liquid Mixture, Vibration Isolation, Vibration Control**

I. INTRODUCTION

In view of the pressing demands for the protection of structural installations, nuclear reactors and machinery equipment, engineers and researchers have developed various types of vibration isolators, such as wire rope isolator, rubber isolator, air spring isolator and enhanced foam isolator [1]-[3] etc. But in some industrial sectors engineers are not satisfied with the existing isolation technologies which leave much to be desired, such as small static load capability, lack of thorough understanding of working mechanism, difficult maintenance process, gas leakage (from air springs) and so on [4]-[5]. For ship engine and other heavy equipment, convenient and easy access for maintenance process is important. Thus it seems logical to develop new vibration isolation technology to meet more challenging engineering requirements.

This paper proposes a new type of nonlinear isolator which uses Solid And Liquid Mixture (SALiM) as working media, as shown in Fig.1. The hydraulic cylinder is filled with SALiM which consists of incompressible liquid and many compressible elastic solid elements. When under shocks or vibrations, the incompressible liquid can instantly pass the pressure from the piston on to all the solid elements in the container, which causes all the solid elements compressed and deformed simultaneously.

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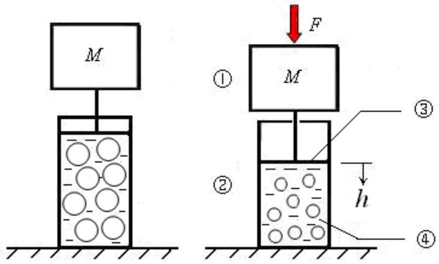
As a result the SALiM can absorb and dissipate the mechanical energy of vibrations and shocks. If designed properly, the isolator could effectively reduce the transmission of the vibration force from the source to the protected devices. The SALiM isolator could have an excellent performance on both vibration isolation and shock absorbing, and it is potentially suitable for the heavy equipment with low natural frequencies.



①Mass; ②Cylinder; ③Piston; ④Solid And Liquid Mixture

Fig.1 SALiM vibration isolator system

The concept of shock absorbing using solid liquid mixtures was put forward by Courtney in 1996 who named it Shock Absorbing Liquid (SALi). He did a systematic experimental study on shock absorbing using the SALi [6]-[7]. According to his study, it was seen that the SALi outperformed the conventional shock absorbing materials. As the further development of the SALi, this paper investigates the possibility of the application of SALiM with improved elastic solid elements to vibration isolation. It is anticipated that the SALiM isolator would have some advantages over the conventional isolation techniques. It could find broad applications in many engineering sectors where the isolation is crucial for structures and equipment.

II. STIFFNESS OF SALIM ISOLATOR

Fig.1 shows a single DOF system subject to excitation force *F*. Hollow rubber spheres filled with pressurized air are used as elastic solid elements. To simplify the process of deriving the nonlinear stiffness of the SALiM isolator, the compressibility of the hydraulic oil and element material are neglected. The coordinates of the initial

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configuration are spherical coordinates which is also used for the deformed configuration. Consider an arbitrary particle P within the sphere wall at R, ϑ, ϕ before deformation, it moves to a new position r, θ, φ at the final configuration. It is assumed that the displacement of P only happens along the radial direction during the deformation so that the deformation remains in the form of spherical symmetry. R_1 and R_2 are the inner radius and outer radius of the hollow sphere at the initial configuration (as shown in Fig.2), where r_1 and r_2 the inner and outer radius of the sphere at the deformed configuration, P_{air0} and P_{air} the initial air pressure and the final air pressure, and P_{oil0} and P_{oil} the initial hydraulic pressure and final hydraulic pressure.

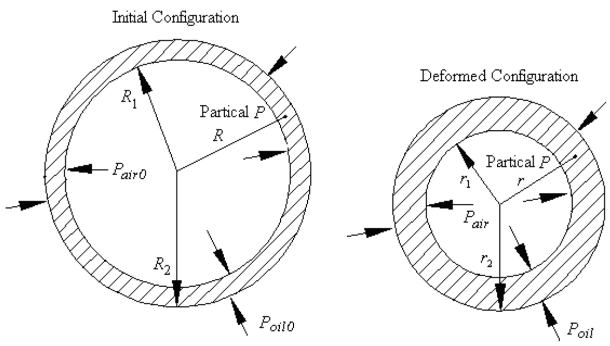

Fig.2 Hollow rubber sphere elements

Under the spherical symmetry assumption, the displacement of P can be described as follows

$$r = r(R)\,, \theta = \vartheta\,, \varphi = \phi\,.$$

The principal length ratio is given by [8]

$$\lambda_1 = \lambda_r = r'\,,\ \ \lambda_2 = \lambda_3 = \lambda_\theta = \lambda_\varphi = \frac{r}{R}\,. \tag{1}$$

The stress in the deformed configuration can be obtained after a cumbersome deriving process as

$$\begin{aligned}\sigma_{r_2} = \sigma_{r_1} - c_1[-5(1+\frac{c^3}{R_2^3})^{-\frac{1}{3}} + c^3R_2^{-3}(1+\frac{c^3}{R_2^3})^{-\frac{4}{3}} \\ +5(1+\frac{c^3}{R_2^3})^{-\frac{1}{3}} - c^3R_1^{-3}(1+\frac{c^3}{R_1^3})^{-\frac{4}{3}}] - 2c_2[(1+\frac{c^3}{R_2^3})^{\frac{1}{3}} \\ +c^3R_2^{-3}(1+\frac{c^3}{R_2^3})^{-\frac{2}{3}} - (1+\frac{c^3}{R_1^3})^{\frac{1}{3}} - c^3R_1^{-3}(1+\frac{c^3}{R_1^3})^{-\frac{2}{3}}]\end{aligned} \tag{2}$$

where c is a integration constant depending on the final configuration, and c_1 and c_2 are the elastic material constants determined by $c_1 = \frac{E}{6}$, $c_2 = \frac{E}{48}$. The force boundary conditions can be described as $P_{oil} = -\sigma_{r_2}$, $P_{air} = -\sigma_{r_1}$. Under the assumption that the liquid in the SALiM is incompressible, the change of SALiM volume is equal to the total deformation of n elements. The nonlinear relation between force and displacement can be established as

$$\begin{aligned}F = (p_{oil0} - p_{air0})s + Kh = (p_{oil0} - p_{air0})s \\ +(k_0 + k_1h + k_2h^2)h\end{aligned} \tag{3}$$

where h is the displacement of the piston, k_0, k_1 and k_2 are constants determined by the geometric and physical parameters of the container and elastic elements.

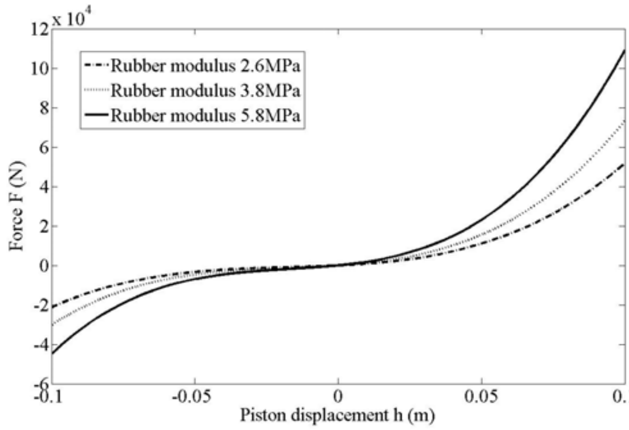

Fig.3 The effect of element material modulus on stiffness

From Eq.(3), it is obvious that the stiffness K of a SALiM isolator is a quadratic function of the piston displacement. Thus, a SALiM isolator should possess nonlinear dynamic properties. If $p_{air0} = p_{oil0}$, the relation curves of restoring force and displacement are as shown in Fig.3, which indicate that they are unsymmetrical about the line of $F = h$ in contrast to a cubic nonlinear system, such as a Duffing's system having a symmetrical restoring force curve.

III. Primary Responses in Time Domain

The vibration system is a SDOF system as shown in Fig.1. The stiffness of the isolator is provided by the SALiM. The static equilibrium position is set as the origin of coordinate system. When due to the contact surface between the piston and the hydraulic cylinder wall is covered by a thin lubricating oil film, it is usual to assume that the friction force is linear viscous damping which is the most common model for modelling of vibration damping. The equation of motion of the SDOF system with SALiM isolator can be written as

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$$M\ddot{x}+c_0\dot{x}+(k_0+2k_1h_0+3k_2h_0^2)x \\ +(k_1+3k_2h_0)x^2+k_2x^3=F_0\cos\omega t \tag{4}$$

where x is the displacement of the mass lump and h_0 the static displacement of piston under the mass weight.

Let $x_1=x, x_2=\dot{x}$ and a constant $x_3\equiv 1$, and Eq.(4) can be rearranged in matrix form

$$\dot{X}=\begin{bmatrix} 0 & 1 & 0 \\ -(\omega_0^2+\alpha_2x_1+\alpha_3x_1^2) & -2c_1 & F_1\cos\omega t \\ 0 & 0 & 0 \end{bmatrix}\begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix} \\ =HX \tag{5}$$

where $\omega_0^2=\dfrac{k_0+2k_1h_0+3k_2h_0^2}{M}$, $c_1=\dfrac{c_0}{2M}$,

$\alpha_2=\dfrac{k_1+3k_2h_0}{M}$, $\alpha_3=\dfrac{k_2}{M}$, $F_1=\dfrac{F_0}{M}$.

Eq.(5) can be regarded as a set of constant coefficient differential equations in interval [t_{k-1} , t_k], $t_k=k\cdot\tau$. Noting that $H_{k-1}=H_{[(k-1)\tau]}$, the general solution of Eq.(5) in interval [t_{k-1} , t_k] can be written as

$$X_{(k\tau)}=\exp(\tau H_{k-1})X_{[(k-1)\tau]} \qquad k=1,\ 2,\ \dots \tag{6}$$

The precise integration method can be employed to solve $\exp(\tau H_{k-1})$ in a time step [9], then the primary response of isolator can be evaluated as shown in Fig.4.

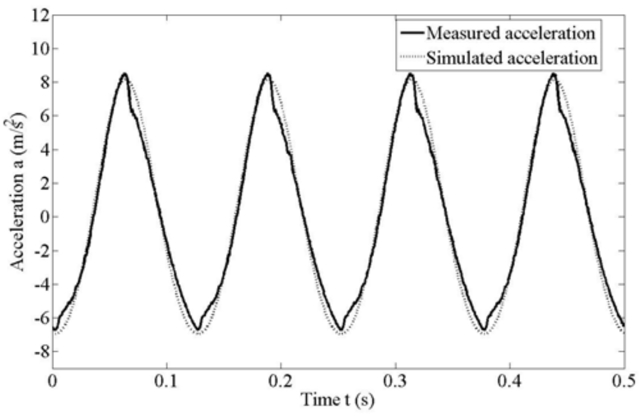

Fig.4 Comparison of acceleration between numerical simulation and measured, *rms*=0.682

A harmonic excitation with resonance frequency of 8Hz is applied to the mass *M*, as shown in Fig.4. The dash line is the simulation result of which the excitation signal is similar to the experimental and the damping ratio is evaluated from the measured frequency response function. It is shown that the simulation is successful in predicting the primary response in the time domain. In general, there is a good agreement between the measured and simulated results. Based on further comparison between the simulated and measured acceleration curves, we can see a rather large discrepancy at the wave crests and troughs. The discrepancies between measured and predicted responses maybe originate from the existing damping model neglecting the friction. The derivation of an improved model will be exploited in the later work.

IV. ENERGY TRANSMISSIBILITY OF SALIM ISOLATOR

For a nonlinear system, a harmonic excitation will not generate pure harmonic response with the same frequency. The response may contain sub-harmonics and super-harmonics, and sometimes the response may even be chaotic. Hence, the force transmissibility makes no sense for a nonlinear system and a suitable performance index for the SALiM isolator should be defined. The energy transmissibility defined in reference [10] is one of the proper definitions:

$$\eta=20\log_{10}\sqrt{\frac{P_T}{P_0}} \tag{7}$$

$$\begin{cases} P_T=\dfrac{\omega}{2\pi}\displaystyle\int_0^{\frac{2\pi}{\omega}}(f_T)^2\,dt \\ P_0=\dfrac{\omega}{2\pi}\displaystyle\int_0^{\frac{2\pi}{\omega}}(f_0)^2\,dt \end{cases} \tag{8}$$

where P_T and P_0 denote the power of the transmission force and excitation force during a fundamental period respectively. Based on the Eq. (4), the restoring force between the vibration source and the base can be written as

$$f_T=c_0\dot{x}+(k_0+2k_1h_0+3k_2h_0^2)x \\ +(k_1+3k_2h_0)x^2+k_2x^3 \tag{9}$$

and the excitation force is assumed as $f_0=F_0\cos\omega t$.

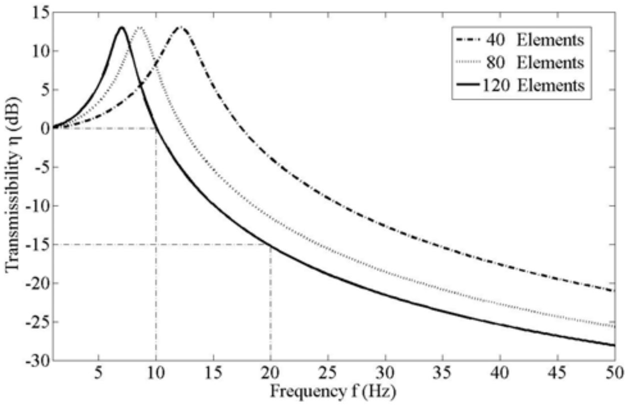

Fig.5 Transmissibility curves of system filled in different amounts elements

Based on the parameters of the test rig as shown in Fig.1, the energy transmissibility of the SALiM was calculated and analysed in frequency domain. It is shown that SALiM isolator has good energy transmissibility as shown in Fig.5. The resonance frequency of the system with 120 elements is 7Hz. The effective isolation region begins at 10Hz. The vibration reduction reaches 15dB at frequency 20Hz.

V. CONCLUSIONS

Based on theoretical analysis, test validation and precise integration simulation, it is verified that the performance of SALiM isolator is sensitive to the material modulus and the number of the solid elements. Its property can be accurately and easily adjusted by altering the quantity of the elements. Therefore, the natural frequency and isolation performance of the isolator can be designed at ping point. Also, it is proved that the precise integration method can be used to evaluate the primary responses in time domain of a SALiM isolation system, and the result has a good agreement with the measured response. The energy transmissibility of a test rig and a simulated isolation system shows that the SALiM isolation system has an outstanding performance and a good prospect in engineering practice.

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