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Improving the Exploitation of Fluid in Elastomeric Polymeric Isolator

Haithem Elderrat, Huw Davies, Emmanuel Brousseau

Abstract**—**Elastomeric polymer foam has been used widely in the automotive industry, especially for isolating unwanted vibrations. Such material is able to absorb unwanted vibration due to its combination of elastic and viscous properties. However, the 'creep effect', poor stress distribution and susceptibility to high temperatures are the main disadvantages of such a system.

In this study, improvements in the performance of elastomeric foam as a vibration isolator were investigated using the concept of Foam Filled Fluid (FFFluid). In FFFluid devices, the foam takes the form of capsule shapes, and is mixed with viscous fluid, while the mixture is contained in a closed vessel. When the FFFluid isolator is affected by vibrations, energy is absorbed, due to the elastic strain of the foam. As the foam is compressed, there is also movement of the fluid, which contributes to further energy absorption as the fluid shears. Also, and dependent on the design adopted, the packaging could also attenuate vibration through energy absorption via friction and/or elastic strain.

The present study focuses on the advantages of the FFFluid concept over the dry polymeric foam in the role of vibration isolation. This comparative study between the performance of dry foam and the FFFluid was made according to experimental procedures. The paper concludes by evaluating the performance of the FFFluid isolator in the suspension system of a light vehicle. One outcome of this research is that the FFFluid may preferable over elastomer isolators in certain applications, as it enables a reduction in the effects of high temperatures and of 'creep effects', thereby increasing the reliability and load distribution. The stiffness coefficient of the system has increased about 60% by using an FFFluid sample. The technology represented by the FFFluid is therefore considered by this research suitable for application in the suspension system of a light vehicle.

Keywords—Anti-vibration devices, dry foam, FFFluid.

I. Introduction

UNWANTED vibrations can raise hazardous conditions in any type of dynamic system, ranging from large multi-storey buildings to small measurement component systems [1]-[3]. Consequently, vibration control has been a point of concern for engineers aiming to improve system performance. The essential features of an isolator are resilient load-supporting characteristics and the opportunity for energy dissipation. The means of providing resilient load-carrying is performed by springs; while the means of energy-dissipation is provided by dampers. In some types of isolators, the functions of the load-supporting elements and the energy-dissipating elements may be performed by a single element, e.g., a layer or natural rubber or other viscoelastic material.

Viscoelastic materials, often termed as elastomeric polymers, are extensively used as a means to mitigate resonant vibration responses. A very common approach is to use pads or sheets made of elastomeric polymer between the base and the movable component. This method is characterized by its low weight, low cost and its ability to be formed into different shaped absorbers. It has been used in many applications, such as automobile car seats, body armor, construction equipment, etc. [4]. However, in certain applications its poor load distribution, creep and high temperature effect is usually the main disadvantages of such material [5], [6]. One solution to minimize the effect of these disadvantages is to implement elastomeric isolators in bonded configurations, where metal inserts are bonded to the elastomer on all load-carrying surfaces. Although the performance of the part is improved, this approach has a higher cost, due to both the additional material and also the processing required because of the special chemical preparation required to achieve a bond with strength in excess of that of the elastomer itself [7]. The solution proposed as part of this research is to mix small particles of elastomeric polymer with a viscous carrier fluid, after which the mixture is contained in an enclosed package. This mixture is a relatively new method that is designed to improve the utilization of the elastomer material, and reduce the early damage due to the concentration of stress in a local area [8]. Both solid dense and foam of elastomeric polymers could be exploited in the design of such a device. However, this research will be focused on elastomeric foamed materials. Specifically, the mixture investigated here is called Foam Filled Fluid (FFFluid). There have already been some applications using this technology, such as the FFFluid shock absorber [9], and vibration isolator [10].

The objectives of this research were to present the advantages of the FFFluid technology over dry elastomeric polymer foam, experimental investigation was carried out to illustrate some of these benefits. Then, the performance of an FFFluid device in the suspension system of a light vehicle was evaluated.

The paper is organized as follows: Section II presents the FFFluid technology; this includes the working mechanisms of FFFluid devices. In Section III, the advantages of FFFluid over dry foam are presented. The performance of the FFFluid suspension system is then evaluated in Section IV, and finally, conclusions are drawn in Section V.

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II. FFFLUID TECHNOLOGY

Solid foamed materials (materials that are made up from a frame work of solid material surrounding gas-filled voids) are increasingly finding application in the automotive industry to carry out safety related functions. In each case the foamed material is able to dissipate large quantities of energy due to the combination of elastic and buckling modes that occur during compression. A further advantage of foamed materials as energy absorbers is that in addition to the energy dissipation that is visible from the mechanical properties of the cell structure, another form of energy dissipation is to be found in the viscous work done to expel the gas from inside the cells of the foam. This mechanism is generally not exploited since most foam materials are filled with air; however, this mechanism becomes important when the air is replaced with a more viscous fluid and at higher strain rates. These materials can be classed as fluid (or liquid) filled foams. A further innovation is foam-filled fluids. Whilst the incompressible fluid component plays a similar role to that in fluid filled foams (absorbing energy via viscous dissipative effects), the manner in which it does so differs. More markedly, when correctly packaged foam filled fluids take advantage of the hydraulic pressure equalization characteristics of the fluid to further alter the mechanical properties and improve the energy absorbing capability of the material. Such a mixture was introduced in 1990s [8]. FFFluid offers several contributions to the fulfilment of a longstanding objective: the isolation of unwanted vibrations. These contributions are:

The properties of elastomer particles: When FFFluid is subjected to a compression load; elastomeric foam is deformed during the loading. An elastomeric polymer with viscoelasticity (having both viscosity and elasticity) has the ability to dissipate energy and provide stiffness to the system during the compression loads [11].

Contribution of gases inside the cell: The use of closed-cell foam or hollow rubber balls provides another mechanism for the isolation of vibration, which is related to the presence of the fluid (gas) inside the cells. The pressure inside the closed capsules changes in response to the change in pressure exerted by the surrounding fluid in the system. Before the load, the elastomeric capsules are in close contact, and an incompressible matrix fluid fills all of the empty space between the capsules; during the load, the ratio of fluid to capsule volume increases as the capsules are compressed from the initial pressure (P_0) to the new pressure (P_1), as shown in Fig. 1. The gas is compressed as the foams deform, storing energy, which is largely recovered when the foam is unloaded.

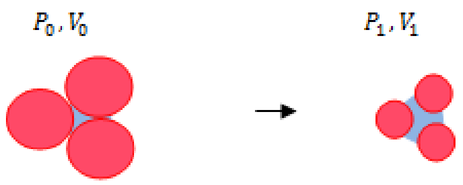


Fig. 1 Compression air inside cells from P0 to P1

Viscosity of the fluid: The main purpose of the fluid in the FFFluid sample is lubricating the device and transferring the stresses throughout all of the foam. When the FFFluid system is subjected to loads, the incompressible liquid is moving around all of the foam elements, thereby distributing the pressures. These movements convert some energy into heat through the viscous effect of the fluid. Fig. 2 shows the rotational movement of the fluid around the compressible foams.

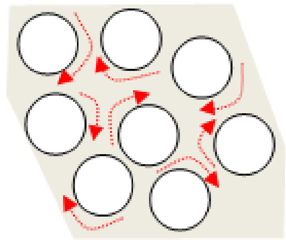


Fig. 2 The viscous liquid swirls around the shrinking capsules, contributing viscous damping to the energy absorbing effect

Contribution of the Package: The final innovative contribution made by this system is its potential positive effect on the packaging of, say, a suspension component. The packaging is itself able to absorb energy due to the viscous effect of its elastic material or due to the friction effect if it is arranged in a piston and cylinder formation.

To summarize the energy isolation process: the energy isolation effect created by an FFFluid composite material occurs through the following mechanisms: one is the work done in compressing the elastomeric material (leading to elastic strain of the material and also compression of the gas within); another is the work done by the matrix fluid as the material shears; and there is additional contribution, which mainly depends on the package used.

III. COMPARISON BETWEEN FLUID AND DRY FOAM

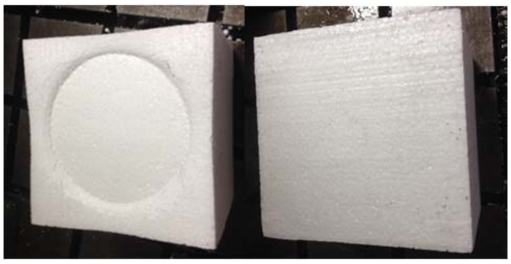
There are several unique advantages of FFFluid mixtures over dry foam in the design anti-vibration devices. The most-apparent advantages of FFFluid over dry foam are presented in the following section:

1-Stress Distribution

Dry foam parts usually fail to distribute a load uniformly under compression or tension load, resulting in local areas of stress concentration in the body, which shortens the life of the isolator. By contrast, FFFluid isolators are able to distribute the load distribution during loading. The fluid in an FFFluid mixture is used to transfer stresses equally among all particles of foam. This prevents the concentration of stress in any local area.

In these experiments, two identical samples of polystyrene (one dry foam and another in FFFluid samples) were subjected to quasi-static displacement (65cm). The dry sample had the dimensions: 120, 120 and 150 mm in width, depth and length, respectively. The result of the application of load is shown in Fig. 3. Fig. 3 (a) shows how the foam displayed deformed plasticity in the area directly placed under the applied force, while the remaining area was not deformed, as is shown in Fig 3 (b).

The FFFluid sample has a cylindrical shape, with dimensions 120 mm (diameter) and 150 mm (length). Compression was carried out under the same conditions as for the previous foam block. Upon removal of the load the foam particles of the FFFluid were inspected and it was observed that they had recovered to their initial volume (Fig. 4).



(a) (b)

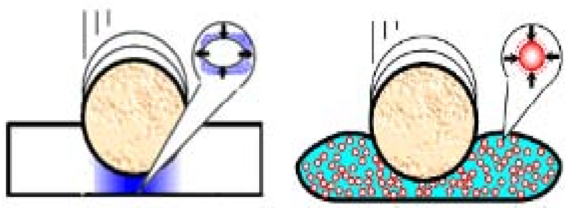
Fig. 3 The sample of dry foam: (a) top area, (b) bottom area

(a) (b)

Fig. 4 The sample of FFFoam: (a) top area, (b) bottom area

2-Axes Loading of the Elastomer Material

When a dry (traditional) foam sample is subjected to quasi-static compression loads, the cells inside the foam are compressed uni-axially. By contrast, in the case of the particles suspended in the FFFluid, the fluid transfers the load equally throughout the surface of all particles. Hence, the foam capsules are compressed multi-axially, as shown in Fig. 5.

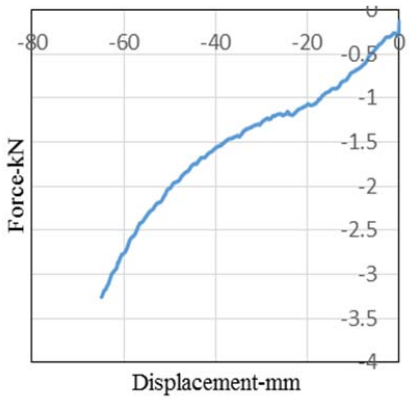


(a) (b)

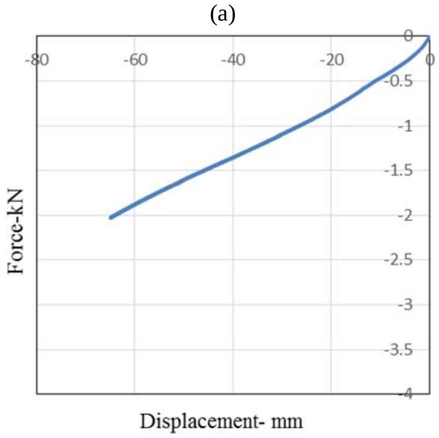
Fig. 5 Foam under compression load: (a) dry foam, (b) FFFluid

In multi-axially loading, the stress caused by one is partly cancelled by the other, and plastic collapse during multi-axially loading occur at least three times higher than plastic collapse during uni-axes loading [12].

Another advantage of multi axis loading is that the foam becomes more resistant to creep phenomena. Creep is one of the main factors than have tended to mitigate against the widespread application of rubber springs in vehicle suspension systems [6]. Creep occurs through the transport of the material via the diffusion of atoms within a grain, which is driven by the difference in potential energy created during the applied stress. For example, applied tensile stress creates regions of high hydrostatic tension along the loading axis at the extremities of each grain. Meanwhile a lower level of stress is exerted in other regions. Since atoms are subjected to different stresses, they will tend to diffuse towards such regions. And this motion will lead to the elongation of the grain along the loading axis. In FFFluid devices, however, the stresses will be fairly distributed around all cells and atoms.



(a)



(b)

Fig. 6 Force-displacement graph of sample: (a) FFFluid sample, (b) Dry Foam

3- Effective Area

The stress of solid material is calculated by dividing the applied load on stressed area (effective area). The difference between the two systems is the effective area. The effective area of the dry sample is the cross section area of the isolator. Meanwhile, the effective area of FFFluid is the surface area of small particle multiplied by the number of particles. Therefore, the FFFluid reduces unit stress by distributing the stress more uniformly throughout the volume of the elastomer.

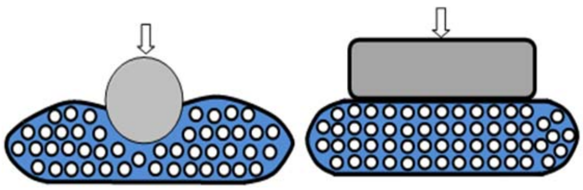
This in turn leads to an increase in the maximum tolerable elastic stress [12].

In our experiments, the reaction load of the previous dry sample reached 2 kN as shown in Fig 6 (a), and effective area was 0.0144 m^2. This sample was plastically deformed under given static displacement. For a similar sample of FFFluid, the reaction load reached about to 3.5kN, which is more than 60% greater than the dry foam's load as shown in Fig 6 (b), and effective area approximately 0.7 m^2. Moreover, foam particles are deformed elastically.

4-Smart Properties

For the purpose of this study, a smart structure is a structure that has the ability to adapt to environmental conditions according to the design requirements. As a rule, the adjustments are designed and performed in order to increase the efficiency or safety of the structure.

A smart structure could be designed by using an FFFluid mixture without any external control system. A vehicle bumper system has been designed by using technology [9]. This structure is able to have a high stiffness in an impact between opposing vehicles, and a lower less stiffness in the case of an impact between a vehicle and pedestrian. With a small impacting body, the elastic fluid is shifted sideways of the impact zone (Fig. 7 (a)). The impacting body would "see" the FFFluid package as a wide, soft cushion. The matrix fluid transmits pressure changes, allowing the elastomeric material to the sides of the impact zone to also participate in absorbing impact energy. A larger object involves a wider contact area during an impact. There would be no movement of the elastic material sideways from the impact zone (Fig. 7 (b)). The rate at which the FFFluid material is crushed will be higher. The FFFluid material will have a higher stiffness.



(a) (b)

Fig. 7 Concept of FFFluid shock isolator: (a) Stiffness (b) Stiffer

5- Temperature

High temperature is known to affect the performance of elastomeric polymer materials. For example, the glass temperature of polystyrene (PS) is about100 C^0. At such temperature, the Young's Modulus of (PS) changes from 1000 MPa to about 1 MPa [12]. The limited operating temperature range is one of the usual disadvantages of elastomeric polymers in practical applications [5], [7]. A thermal advantage of using FFFluid instead of elastomeric foam is that a matrix liquid with good thermal conductivity can be included to help dissipate heat. The package could also be designed specifically (by adding cooling fins, for example) to dissipate the heat outside the package.

6- Sustainability Device (Environmental Considerations)

Three has been a significant increase in the amount of elastomer scrap produced every year, such quantities of elastomeric polymer foam scrap - comprising discarded packaging and industrial waste - constitute a real environmental threat. It has been suggested that this device could be manufactured using such industrial scraps, the result being that the device may be produced in a low cost and eco-friendly way. An additional appealing characteristic of FFFluid devices is that they can be recycled cold; the used mixture of fluid and foam can be re-used, by placing them directly in any other FFFluid devices.

7-Package

Packaging is one of the main components of an FFFluid device. It is used to maintain the blend of the FFFluid. The packaging itself could be elastic packaging - such as stout cotton bags; or stiff packaging - such as piston and cylinder arrangements. Although elastic packaging provides an extra elastomer material for the purpose of dissipating energy, there are advantages to using stiff packaging, namely:

Stiff packaging provides a higher buckling resistance than a dry elastomer. Therefore, devices that have high ratios between lengths to width and depth could be designed using an FFFluid mixture, while it is not possible to produce such devices using dry foam. Also, designs incorporating FFFluid within a stiff package are capable of coping with bulges in the elastomeric polymer. The bulge may not be considered a significant issue in the use of elastomer pads in the dry workplace. However, if the workplace is oily or sandy, the bulge between elastomer and metal can cause malfunction of the isolator [7].

IV. Performance of FFFluid System

Previous studies into FFFluid isolators were configured so as to determine the stiffness and damping coefficients of the system. Accordingly, the force transmissibility of the FFFluid system was defined based on these values [10]. Different values of stiffness and damping coefficients could be achieved based on the input parameters, therefore such system could be designed in different application. One of these applications is a suspension system for the L7e light vehicle, it is noticed that the values of the spring and damper coefficients of the FFFluid system by using PE-70 could be used in designing such a system [13]. Therefore the performance of FFFluid as suspension system will be evaluated; this result can be compared with the real values from the behaviour of the suspension system in the L7e vehicle.

The roles of a suspension system are to support the vehicle weight, to isolate the vehicle body from road disturbances, and to maintain the traction force between the tire and the road surface. Therefore, in order to use the FFFluid isolator in this way, as shown in Fig. 8, the quality of suspension system should be scrutinised according to additional criteria, namely:

The ride comfort, this value could be expressed as $\ddot{x}_2$ in Fig 8. And suspension displacement, this defines the suspension travel range and also the design requirement for suspension space and it could be expressed as $x_2 - x_1$ in Fig. 8.

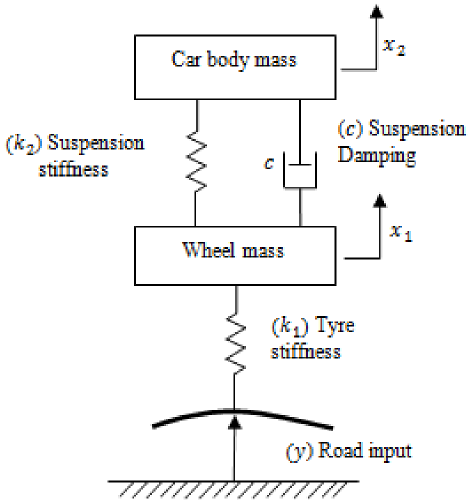


Fig. 8 Suspension system of quarter vehicle

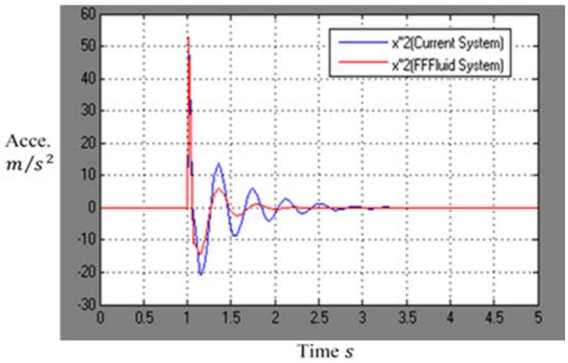


Fig. 9 Ride comfort

These criteria will be measured using the Simulink tool in MatLab. The FFFluid isolator has stiffness 32 kN/m and damping 1590 $N.sec/m$ [10]. Such system have the next value [13]: Tire stiffness (k_1) 110 kN/m, Suspension stiffness (k_2) 44.7 kN/m, Suspension Damping (c) 1031 $N.sec/m$, Wheel mass 5 kg, Car body mass 50 kg. The input signal of the suspension system was step input with amplitude0.1 m.

The vehicle responses are displayed in Figs. 9 and 10. The proposed suspension system produces suitable performance as suspension system; we can observe the reduction of the driver's vertical displacement peak, and peak deflection of the suspension system. Moreover, the FFFluid system was much better in term of other criteria such as ease of design and light weight and low cost [10]. There is usually a certain degree of complexity in designing springs and dampers. By contrast, the manufacturing of FFFluid systems is easier than these traditional isolators, as it does not require a precision engineered spring and hydraulic seal, and also because it has fewer moving parts.

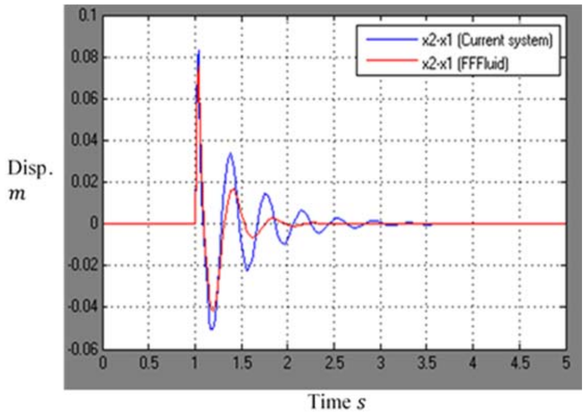


Fig. 10 Suspension system deflection

V. Conclusions

Elastomeric polymer foam has already been used widely in safety and anti-vibration devices for the automotive industry. It is able to dissipate a large quantity of the energy that occurs during such loads. However, polymeric foam is not an appropriate material for use in certain applications, such as high temperature applications or high stress load applications. This paper constitutes a valuable investigation into the utilization of the fluid in foam isolators, offering a useful comparison between dry foam and FFFluid. It is concluded that FFFluid does indeed have characteristics appropriate for implementation in vibration isolator designs. FFFluid technology possesses several characteristics offering advantages over dry foam. Furthermore, it is preferred over elastomer isolators, because it allows local stress effects to be reduced and reliability thus increased. And, compared with dry foam, it has a higher ability to carry loads 60% higher than dry foam. Suspension systems employing FFFluid can potentially provide performance advantages over traditional spring / damper systems.

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