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INVESTIGATION OF THE FOAM FILLED FLUID TECHNOLOGY FOR ANTI-VIBRATION DEVICES

[Haithem Elderrat, Huw Davies, Emmanuel Brousseau]

***Abstract*— In this study, Foam Filled Fluid (FFFluid) technology was investigated for the design of a novel vibration isolator, which is referred to as an FFFluid isolator. This technology relies on the utilisation of both the strain of foam capsules and fluid motion for reducing unwanted vibrations. Such an FFFluid isolator basically consists of compressible elastic particles of foam, mixed with an incompressible fluid while this mixture is contained in a controlled volume. When the FFFluid isolator is affected by vibrations, energy is absorbed due to the elastic strain of the foam. As the foam strain also enables movement of the fluid, this contributes to further energy absorption due swirling and the viscous effect of the fluid. The packaging could also contribute to attenuate vibration through the generated friction between the piston and the cylinder used to contain the FFFluid. Former studies showed that promising performances in reducing unwanted forces can be achieved with shock absorbing devices using the FFFluid technology. Such studies also highlighted the importance of defining key parameters of FFFluid devices properly. The present study was focused on characterising the FFFluid technology for vibration isolation. The performance of the system was determined based on experimental data in order to assess the stiffness and damping coefficients of the developed device.**

***Keywords*—FFFluid, Vibration Isolator**

I. Introduction

Vibrations can be utilized in many applications. However, for most of the time the presence of vibrations causes several issues in mechanical systems, such as decreasing the quality of manufactured products, producing noise, generating fatigue in mechanical components and others [1]. For these reasons, the theory of vibrations within an engineering context has been studied for over a century, and it is still a major engineering concern in the design of mechanical systems [2, 3]. There are several ways for controlling unwanted disturbances [2], one of these methods consists of inserting devices between sources of vibration and systems. These devices, called vibration isolators, help to attenuate problems arising from vibrations. Various types of anti-vibration devices have been designed previously [4, 5]. These isolators were developed using different concepts such as; elastomer isolators [6], controllable isolators (isolators with control systems) [7], pneumatic isolation systems [8] and others [9, 10]. Although there are a variety of methods for designing practical vibration isolators, the design of alternative novel isolators is still an area of active research. This is due to the increasing demand for anti-vibration devices, and to limitations with respect to cost and size, for example of current isolators in some applications especially for light automobile applications. For instance; air leakage is admitted in most types of pneumatic systems, and this issue causes to reduce performance of isolators quickly [8]. High cost and low reliability are the main problems for almost any controllable isolation system [11]. High temperature and local stress are disadvantages of viscous-elastic materials such as natural rubber, elastomer and foam material [12].

Foam Filled Fluid (FFFluid) is a composite material used for eliminating unwanted forces. It is made of a blend of polymeric foam capsules and a fluid contained in a closed package. Due to the viscoelastic effect of polymeric foams and the viscous effect of fluid, Foam Filled Fluid has the ability to reduce the effect of vibrations. Some applications have been designed using this technology such as vehicle bumper systems [13] and shock absorbers [14]. Designing a vibration isolator by using a similar method was also investigated [15]. However, the contribution of attenuating energy due to the viscous effect of fluid was not accounted. The polymeric foam will be used due to its low cost and availability. This paper has investigated the possibility of characterising FFFluid isolators. The objectives of this research were: (i) to present advantages of FFFluid technology over other existing technologies (ii) to carry out initial experimental works to evaluate the performance of an FFFluid isolator.

The paper is organised as follows: section II presents the FFFluid technology; this includes its components and the working mechanism of FFFluid devices. This is followed by presenting the advantages of FFFluid isolators over current vibration isolators in section III. In section IV, the methodology of characterising FFFluid isolator is described, then the experimental procedures and results analysis are explained in sections V, and VI respectively, and finally conclusions are drawn in section VII.

Haithem Elderrat - Huw Davies - Emmanuel Brousseau.
Cardiff School of Engineering /Cardiff University United Kingdom

II. FFFluid TECHNOLOGY

The composite material described in this paper can be considered as a liquid analogy to elastomeric foams; it is called Foam Filled Fluid and termed FFFluid. This technology is a blend of viscoelastic capsules and a liquid which are kept in an enclosed package. FFFluid is a technology for eliminating unwanted forces which was introduced in 1997 [14]. Several experiments using FFFluid were conducted to validate the shock absorbing property of the technology [14, 16]. Davies also recently designed a vehicle bumper system using the FFFluid mixture [13]. This technology has given promising performances and it also has the potential to solve several issues of existing vibration isolators. Foam Filled Fluid is a mixture that utilized the viscoelastic behaviour of polymeric foam material, the viscous effect of fluid motion and contraction of packages for eliminating unwanted forces. An FFFluid system consists of three main components:

The polymeric foam capsules: A polymeric foam is made up of an interconnected network of solid struts or plates which form the edges and faces of cells. The foam material may be open or closed gas-filled capsules (cellular solid structure). Such foam is able to dissipate large quantities of energy because of a combination of elastic and buckling modes that occur during loading [12], therefore they possess suitable properties to design an anti-vibration system. Polystyrene and polyethylene are examples of foam that are used in FFFluid shock absorber [13, 14].

The matrix fluid: The fluid inside the FFFluid blend has two main purposes; it is used to transfer pressure equally around all foam particles and it attenuates a certain amount of energy by its viscous properties. In addition, the fluid is able to minimise the effect of high temperatures on polymeric foams in cases where the temperature is raised for a given application [14]. Any liquid which is able to hydraulically transfer pressure changes is potentially usable in the FFFluid technology. However, liquid must not have any chemical effects on any other parts of the FFFluid devices. Examples of fluids used previously are silicon oil and aviation oil [13, 15].

The closed package: This is a container to encapsulate the mixture of foams and fluid. Therefore the pressure is transferred from the package to foam particles via the matrix fluid. Moreover, it may dissipate a certain amount of energy. The package used previously varies from stout cotton bags to piston and cylinder arrangements [16].

When FFFluid is subjected to a compression load, the polymeric foam will be deformed during this loading, as the foam capsules are absorbing energy through elastic and buckling characterisation [12]. Then the matrix fluid will swirl around the compressed foams, this movement will convert some energy into heat through the viscous effect of the fluid. The package is also able to absorb energy. This is due to the viscous effect of the package if it is made of elastic material, or due to the friction effect if it is made of a piston and cylinder arrangement. Fig. 1 shows the concept of the FFFluid isolator.

III. ADVANTAGES OF FFFluid

There are several unique advantages of FFFluid mixture over current technologies for eliminating vibrations. The advantages of Foam Filled Fluid over hydraulic isolators (metal springs and dampers) are presented below:

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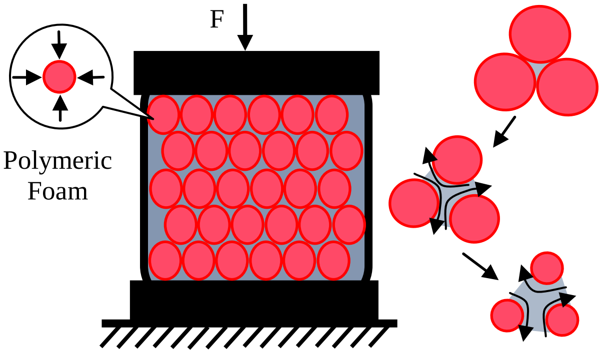

Figure 1: Concept of Foam Filled Fluid mixture.

- Low weight: Although the package of FFFluid may be made of relatively heavy materials, the main components are polymeric foam elements. These components have low densities in comparison with dense material [12]. Therefore, replacing an amount of fluid with foam materials that contain gas voids, leads to weight reduction of the devices.
- Ease of design: There is usually a certain degree of complexity in designing spring and dampers, and this complexity is increased when using a controllable isolator. However, manufacturing of FFFluid systems are easier than these traditional isolators, as it does not require a precision engineered spring and hydraulic seal, and it also has less moving parts.
- Cost: Beside the ease of designing an FFFluid device, it is composed of low cost and easily available materials, therefore the cost of the FFFluid system is usually low compared with other applications. The design of a low cost FFFluid buffer is proposed in [14].

FFFluid also has advantages over other viscoelastic materials such as foam, rubber and Fluid Filled Foam (FFFoam) materials as described below:

- Package: The blend of FFFluid is maintained in a package, and this package provides FFFluid a higher buckling resistance than a dry elastomer. Therefore, devices that have high ratios between length to radius could be designed using this mixture.
- Temperature: Rubber material is sensitive to temperature; therefore such a material is not preferable in applications where the temperature is raised. However, with FFFluid systems, the fluid is used to cool polymeric foam material. Therefore the effect of temperature will be minimised in FFFluid system.
- Local stress: Fluid in an FFFluid mixture is used to transfer pressure equally around all polymeric foams. This

prevents any area of local stress concentration, which in contrast could occur with dry foams as shown in Fig.2. Also cells inside dry foam are compressed uniaxially, while these cells in FFFluid are subject to a stress distribution on their surfaces. This lead to increase the maximum elastic stress.

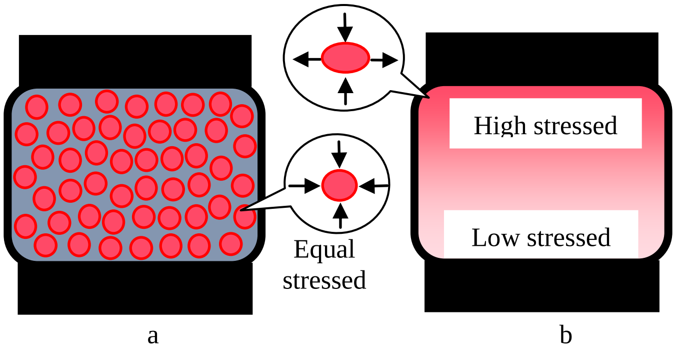

Figure 2: Foam under compression load: (a) FFFluid, (b) dry foam

IV. METHODOLOGY

As explained earlier, FFFluid devices consist of three different materials. These components lead to complex mechanical behaviour which is why the performance of previous applications of FFFluid was determined experimentally. This research also focused on an experimental approach. The steps to characterise a number of FFFluid parameters were; design of the test rig and selection of suitable package for the FFFluid isolator; design and completion of experiments; and the final step consisted of analysing the results and examining the performance of the developed system.

Due to the fact that the investigation was focused on characterising the FFFluid mixture under dynamic loads, a controlled volume package (piston and cylinder arrangement) was used. The test rig was designed to be used for medium size applications. The test rig had a length 300mm, a radius 50mm, and the volume of FFFluid sample was 1 litre. The mixture was made of polyethylene elements at density $70\ \mathrm{Kg/m^3}$ and silicon oil 1000cSt. Experiments were performed on a Servo Test System, which was equipped with a load cell and a software for continuous data acquisition. The test rig was fixed onto the Servo Test System as shown in Fig 3.

Figure 3: Set-up test rig on Servo Test System.

V. EXPERIMENTAL PROCEDURES

Initially, the foams deform elastically under low forces, then they deform plastically when the load is increased. Hence the maximum load applied on the test rig must not reach the plastic region. Before applying force on the test rig, it is necessary to determine the maximum elastic stress of foams particles. The elastic stress of polymeric foam under single axis loading (σ_{el}^{*}) is dependent on the relative density and the Young's Modulus of the foam, and it could be determined by the following expression [12].

$$\sigma_{el}^{*} = 0.05E_s\left(\frac{\rho^{*}}{\rho_s}\right)^2 \qquad (1)$$

Where: ρ^{*} is the density of the foam, ρ_s is the density of material that made foam, E_s is the Young's Modulus of material made foam. Hence, the maximum elastic force F_{max} for the piston that has a radius r is:

$$F_{max} = \pi r^2 * 0.05E_s\left(\frac{\rho^{*}}{\rho_s}\right)^2 \qquad (2)$$

Thus, using polyethylene at a density of $70\ \mathrm{kg/m^3}$(PE-70), the foam is able to carry a load of 1.5 kN during uniaxial compression. In the case of biaxial loading, there are two perpendicular stresses acting in cells, the stress caused by one is partly cancelled by the other , therefore and elastic region can be larger by 10 to 100 times during biaxial loading [12]. Therefore it can be assumed this FFFluid sample is able to carry at least 15kN in its elastic region. The experimental procedure adopted is below:

Test 1: The dynamic load was applied to the test rig without the FFFluid blend. This test was conducted to characterise the friction between the cylinder and the piston. The results of this test are shown in Fig 4. It noticed that about 0.2 kN of force is damped due to this friction force.

Test 2: In this set, the cylinder was filled with FFFluid. Then, a static load was applied to the test rig. The applied displacements ranged from 0 to 55 mm. This second series of tests was conducted to check the presence of oil leakage from the test rig under maximum applied displacement.

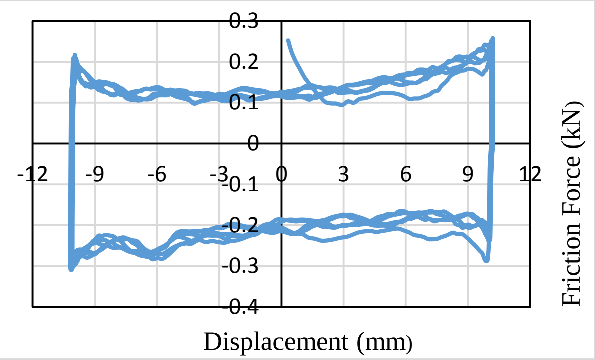

Figure 4: Displacement- Friction force graph of the test rig.

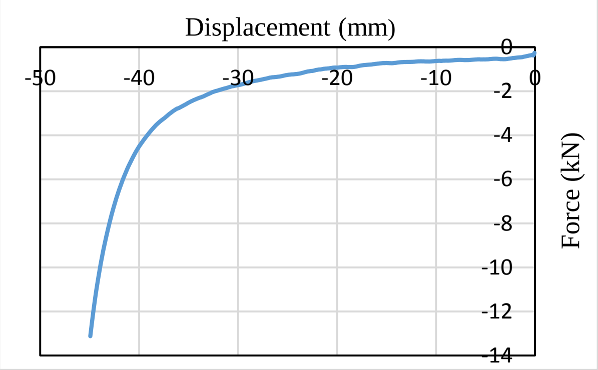

Figure 5: Displacement- Force graph of FFFluid under static load.

In addition, the stiffness coefficient of the test rig could be calculated from this test. Fig. 5 shows the results obtained. The initial observation based on these results is that the system has a linear behaviour at low displacements, while it is nonlinear for displacements higher than 30 mm. This nonlinear behaviour of FFFluid resulted from strained polymeric foam and compressed air inside voids. Both of these materials (strained polymeric foam and compressed air) have nonlinear behaviour [12, 17]. Overall, this characteristic makes FFFluid mixture useful for designing vibration isolators.

Test 3: A dynamic displacement was applied to the FFFluid isolator. In particular, two displacements ± 10 and ± 20 mm were applied at three different values of frequencies: 0.5, 1 and 2 Hz. These values were chosen to examine the mixture in the linear region as initial experiments. This series of tests aimed to investigate the behaviour of an FFFluid isolator under dynamic loads. Fig. 6. shows the results of applying dynamic load at frequency 1Hz. The hysteresis loop due to absorbing energy is clearly observed in this Fig.

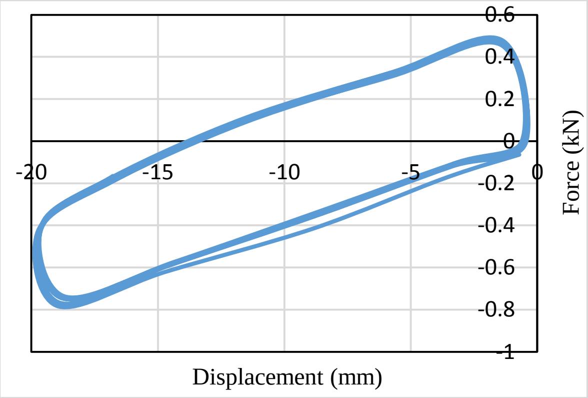

Figure 6: Displacement- Force graph of FFFluid under dynamic load.

VI. RESULTS ANALYSIS

In this isolator, in addition to the foam and the fluid, friction force between the piston and the cylinder also contributes absorbing unwanted vibrations. The equation of motion single degree of freedom is: 74

$$F = m\ddot{x} + c\dot{x} + kx \mp F_{Fr} \tag{3}$$

Where: m is the mass of the system, k is the stiffness coefficient, c is the damping, x is the displacement, $\dot{x}$ is the velocity and $\ddot{x}$ is the acceleration. The value of friction is determined from test 1. As illustrated in Fig. 3, it was determined that the friction force was $F_{Fr} \cong \mp 0.2$ kN.

The stiffness of isolator values were determined from Fig. 4. The test rig has a linear stiffness at low displacement. This value was calculated experimentally and it is equal to $k = 32$ kN/m. However, the test rig behaved nonlinearly at higher amplitude of displacements. The nonlinearity of hardening stiffness is a symmetrical polynomial function. It is equal to $k = 2.1x + 19$ kN/m.

The last parameter is the viscous damping coefficient. This factor can be determined by plotting the graph of displacement against viscous damping. Referring to equation 3, by knowing the friction force and stiffness force, the viscous force could be determined. Fig. 7 shows the relationship between the displacement- viscous force graph by using a linear value of stiffness coefficient. The viscous force was measured from this Fig. and was found to be 0.1 kN. The acceleration of system was $\ddot{x} = 0.059$ mm/sec^2 system. Thus the damping coefficient of the system was found to be $c = 1.68$ kN.sec/mm.

The experimental procedure were also conducted by using polyethylene at two other densities; 30 kg/m^3 (PE-30) and 120 kg/m^3 (PE-120). The results obtained with foams from different foams densities are displayed in Table 1.

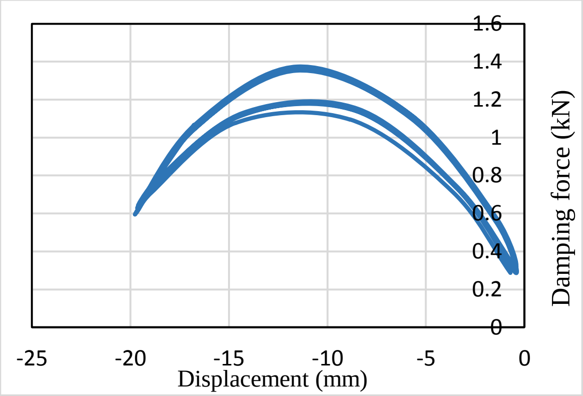

Figure 7: Displacement- viscous force graph of FFFluid under dynamic load

Table 1: Parameter of FFFluid of different foams.

Density kg/m^3	Stiffness kN/m		Damping coefficient $N.sec/m$
	Linear	Non-Linear	
PE -30	21.9	$2.1x + 47$	560
PE -75	32	$1.5x + 20$	1590
PE-125	35	$2.3x + 39$	4850

To assess the performance of isolators, the force transmissibility is usually used for linear systems. It is the ratio between force input and force output, which should be less than one to reduce vibrations. In this research, due to the fact that the applied displacements were low, and this system is a linear behaviour at low displacement, the force transmissibility can be used. For a system with one degree of freedom, the transmissibility is expressed as the next expression:

$$T_f = \frac{F_T}{F_0} = \sqrt{\left\{\frac{k^2+\omega^2c^2}{[(k-m\omega^2)^2+\omega^2c^2]}\right\}} \qquad (5)$$

Where: T_f is the force transmissibility, F_T is the transmitted force, F_0 is the applied force, ω is the natural frequency, k is the stiffness coefficient, and c is the damping coefficient. Fig.8 shows the evaluation of the transmissibility as a function of the frequency ratio r which is a ratio between natural frequency and applied frequency. According to the results, transmissibility is less than one at a frequency ratio more than 1.4, and the amount of transmissibility is improved at higher frequencies.

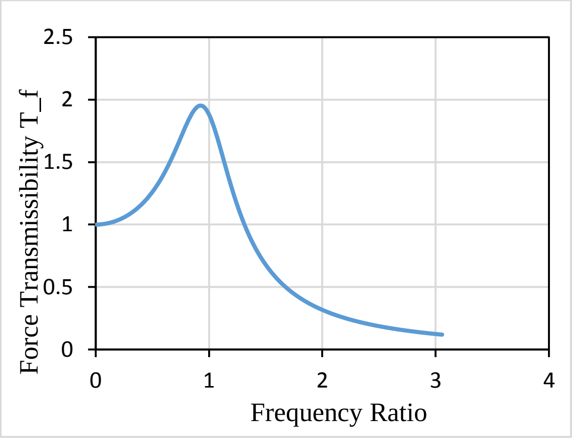

Figure 8: Transmissibility of FFFluid isolator.

VII. CONCLUSIONS

A preliminary investigation on the FFFluid isolator was reported in this paper. It is concluded that the Foam Filled Fluid has the appropriate characteristics for designing vibration isolators. The technology FFFluid possesses is a suitable characteristic which can have advantages over other approaches. Due to the working mechanism of FFFluid technology, such isolators are easy to design and have reduced weight compared with springs and hydraulic dampers. It is also preferable over elastomer isolators as temperatures effects can be reduced and the reliability increased. The coefficients of the system were defined experimentally, and the energy transmissibility of the developed test rig was determined. The FFFluid isolation system has a promising isolation performance and thus is a useful prospect in engineering practice.

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