SHOCK ABSORPTION USING FOAM IMPREGNATED WITH SHEAR THICKENING FLUIDS.

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Abstract
Shear thickening fluids (STF) show an increase of viscosity at a critical shear rate. This increase of viscosity is associated with an important absorption of energy that can be used for vibration control or shock protection. In the present work, shock absorbers effective in shear, made of foam impregnated with STF, have been used to protect a CubeSat. Shock tests consisted in impacting with a hammer the support platform of the suspended CubeSat. Shock response was measured using accelerometers. Shock response spectra are presented and show that STF offer a good protection to the high frequency component of the shock wave.

1 Introduction

The separation of the different stages of multiple stage carrier rockets using explosives generates large shock waves, which can damage the payload if the waves are transmitted through the rigid composite structure. Shock absorbers are thus needed. In general, elastomeric materials are inserted between structural elements. They are however not very efficient for pyrotechnic shock solicitations. We propose to explore an alternative approach for shock control by introducing damping elements containing Shear Thickening Fluids (STF).

STF belong to the class of passive smart materials that could be used to tune both damping and stiffness properties of structures. At a critical shear rate and for a given level of stress, the viscosity of STF increases by up to 3 orders of magnitude, from a honey-like liquid to a solid brittle material. STF have been widely investigated in terms of their rheological properties [1,2]. Shear thickening is a reversible phenomenon, as the transition from high to low viscosity after the end of a dynamic solicitation is instantaneous for colloidal suspensions. As an example, highly concentrated dispersions of silica particles in polyethylene glycol present excellent shear thickening properties.

The theory describing the shear thickening behaviour in suspensions relies on the formation of agglomerates, known as hydroclusters. At stresses under a critical value, particles in suspensions move away from each other due to repulsive interparticle electrostatic or Brownian forces. The action of these forces results in a stabilized dispersion of the particles. The colloidal suspension has a low viscosity when particles are well dispersed and can avoid each other to flow without difficulty. With an increase of external stress and flow, hydrodynamic forces increase and tend to move the particles closer. When the hydrodynamic lubrication forces become higher than the repulsive forces, the particles aggregate into clusters [3].These aggregates limit flow and explain the strong increase of viscosity observed at a critical shear rate. When hydrodynamic forces decrease, hydroclusters break up and the viscosity drops back [4]. Rheological properties of monodisperse particles STF are governed by parameters like the viscosity of the fluid, the particle concentration or the size of the particles [5,6]. For instance, a suspension of silica spherical particles of 500 nm diameter in polyethylene glycol (PEG) with a molecular weight of 200 g.mol^{-1} exhibits shear thickening properties for a concentration of particles between 67 and 68 % w/w. STF are fluid or solid in function of the solicitations from their environment. The rise of viscosity between these two states is associated with large energy absorption that can be used to absorb energy from shocks or vibrations. The energy dissipation is due to the friction between hydroclusters, and increases during the transition [7].

As a result, applications for STF are integration in shock absorbers [8,9], in structures such as skis to tailor both their damping and stiffness properties [10] or in ballistic vests known as “liquid armour” [11]. STF are liquid at rest, hence they need to be contained for practical purposes. To bring a 3D structure to STF, different methods have been proposed as integration into open cell foams [12] or inside a damper [8].

In this work, we propose a practical solution to use foam impregnated with STF in a shock absorber. A shock absorber using Smactane, a widely used elastomeric damping material is also tested for comparison purposes. The setup and the results of the shock tests are presented and discussed.

2 Materials

2.1 Shear thickening fluids

The STF used are highly concentrated colloidal suspension of monodisperse silica particles. The particles were dispersed in polyethylene glycol (PEG) with an average molecular weight of 200g.mol^{-1}. They had an average diameter of 500 nm and were provided by Nippon Shokubai Co. under the reference KE P-50. The PEG was purchased from VWR. PEG and particles were dried at 60 °C under vacuum during two days to eliminate possible residual water content due to contamination by humidity of air. The PEG was then added to the particles and hand mixed until a homogeneous mixture was obtained. After this step, the STF was placed in an ultrasonic bath for three hour at 50 °C (ref. Bandelin Sonorex Super DK-510P 35 kHz, 450 W). Sonication dispersed the particles homogeneously, broke the eventual aggregates and removed the air bubbles due to hand-mixing. A concentration of 67.5 % weight by weight (w/w) was used. The STF was stored in a freezer at -20 °C prior to foam impregnation to avoid premature ageing in contact with air and/or humidity. The flow viscosity of the STF used in this work is presented in figure 1.

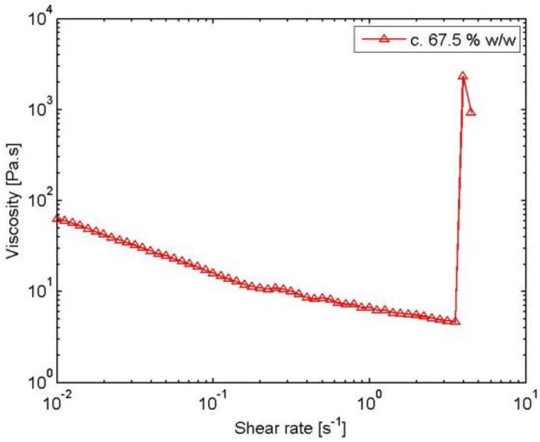

Figure 1. Steady state flow viscosities of monodisperse STF KEP-50/PEG200 c.67.5% w/w

2.2 Open cell melamine foam

The flexible, open cell melamine resin foam manufactured by BASF under the name BASOTECT® UL was used as a lightweight scaffold. The foam distributes the load and locally shears the STF. The density of the foam was 6 kg.m^{-3} and the average pore size between 100 and 150 µm.

2.3 Smactane

Smactane® SP is a viscoelastic rubber material developed by SMAC for space applications. It is widely used in high-end industries for vibration control and shock absorption.

3 Shock tests setup

3.1 General description

An overview of the setup used to perform the shock test is presented in figure 2. The objective is to protect a small structure which is a mass dummy (a) of the CubeSat SwissCube from shock solicitations. The CubeSat is mounted on a support plate (b) which is suspended using polyester wire (c) for decoupling. At the interface between the two, shock absorbers (d) in pure shear have been mounted. The support plate is impacted with a hammer at a controlled force at an impact point (e) far enough to generate a far field shock. Different hammer heads have been used in order to adjust the shock characteristics. The shock response was measured using two accelerometers (f), one fixed on the CubeSat, one on the support plate.

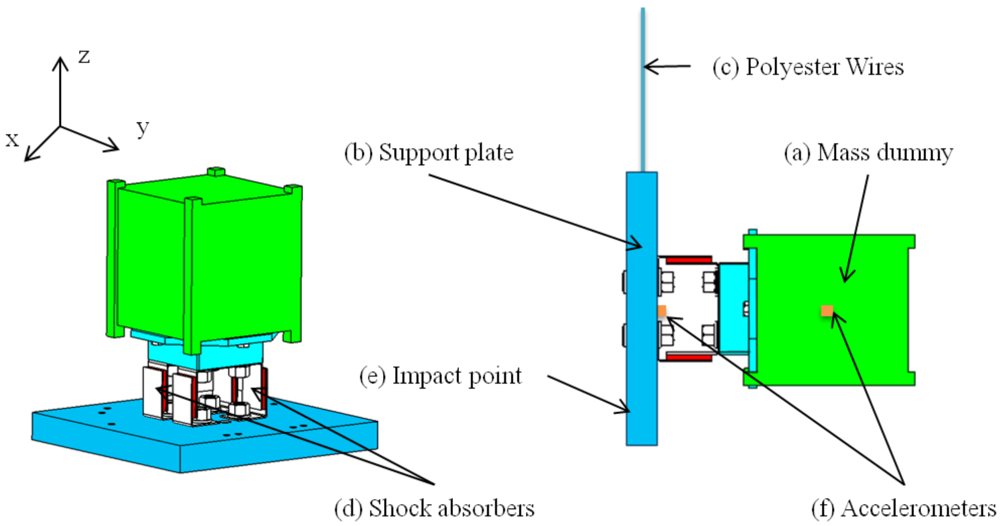

Figure 2. Setup used to perform shock test to measure the efficiency of STF shock absorber

3.2 CubeSat

CubeSat are miniaturized satellites used for space research with a volume of one litre and a weight of less than 1.33kg. The mass dummy is a four walled machined aluminium part. It weighs 860g and it dimensions are 113*100*100 mm. It has the same weight and centre of inertia as the CubeSat SwissCube. SwissCube is a successfully launched CubeSat developed at EPFL to study the airglow phenomena *[13]*.

3.3 Hammer

An instrumented impact hammer, type 8206-002 from Brüel & Kjaer, has been used to generate the shock waves. Impact forces up to 2200 N are measured. By changing the hammer head, different shock waves can be generated as presented in figure 3. Tips used are:

- Rubber: low impact force, low acceleration, long impact, low frequency spectrum, close to a half-sinus shock wave;
- Plastic, similar as aluminium with a slightly longer impact duration;
- Aluminium: high impact force, high acceleration, short impact, wide frequency spectrum, if metal/metal impact: close to a pyroshock [14].

The main difference between the hammer tips is the frequency spectrum of the shock wave. The effective seismic mass was 100g.

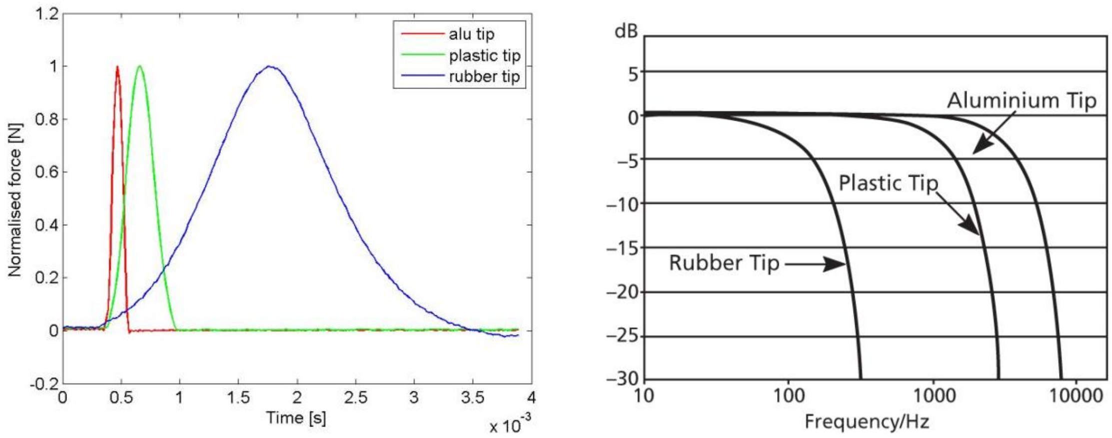

Figure 3. Impulse shapes for the different hammer tips (left) and typical frequency spectrum for an impact on aluminium plate (from B&K datasheet) (right)

3.4 Shock absorbers

Shock absorbers were damping pads placed in sandwich between stainless steel plates with a thickness of 1mm as presented in figure 4. The dimensions of the damping pad were: 30*5*20 mm. They were constituted of Smactane or Basotect UL foam fully impregnated with STF (foam/STF). Damping pads were thus solicited in pure shear.

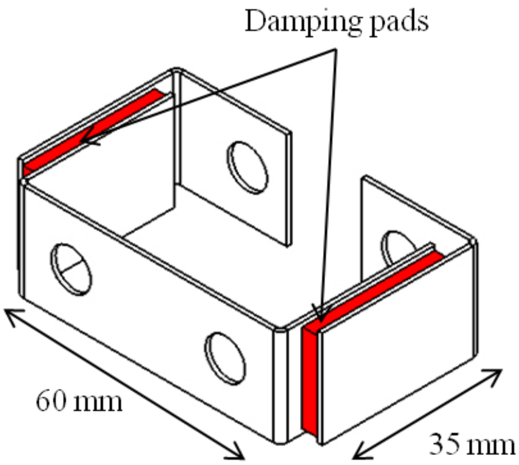

Figure 4. 3D representation of the shock absorbers

The damping pads were glued to the plates with cyanoacrylate glue. The foam of the foam/STF damping pads was glued before impregnation. Foam impregnated with STF by a succession of compression/absorption cycles. Shock absorbers in were then screwed to the support plate using a torque wrench set at 5 kN (Figure 2).

4. Shock data acquisition and treatment

4.1 Data acquisition

Shocks have been measured using two piezoelectric accelerometers with integrated electronics, type 4507 from Brüel & Kjaer, with a maximum measuring range of 71 g. One of them was mounted in the middle of the support plate on the opposite side of the impact, the other one was fixed close to the centre of inertia of the CubeSat (Figure 2). The measuring direction was the z axis (Figure 2). Prior to mounting accelerometers, the mating surfaces have been cleaned using ethanol. A high degree of surface contact between accelerometers and the structure was obtained using honey wax. Loose cables were tied down using adhesive tape. Acceleration was acquired using Virtual Bench DSA from National Instruments.

4.2 Shock response spectrum

The shock response spectrum (SRS) is a graphical representation of the response to a shock.
It is a calculated function, corresponding to the response to a given acceleration of an infinite set of single-degree-of freedom oscillators, each with a unique quality factor. A Q factor Q=10 is conventionally chosen. SRS should be globally increasing [15]. SRS allows comparing shocks with each other by calculating the shock effect on a dynamical standardized system. SRS have been calculated with MATLAB using a slightly modified version of the srs.m script provided by T. Irvine [16].

4. Results

4.1 Shock accelerations

Figure 5 shows the temporal response of shock applied to the structure with the foam/STF shock absorber. Experimental results show a low frequency oscillation of the accelerometer on the mass dummy presumably owing to the low stiffness of foam/STF in regard to the weight of the mass dummy. This component is not observed for the system with the Smactane shock absorber. The response to impact with the plastic tip is very close to the one with the aluminum tip.

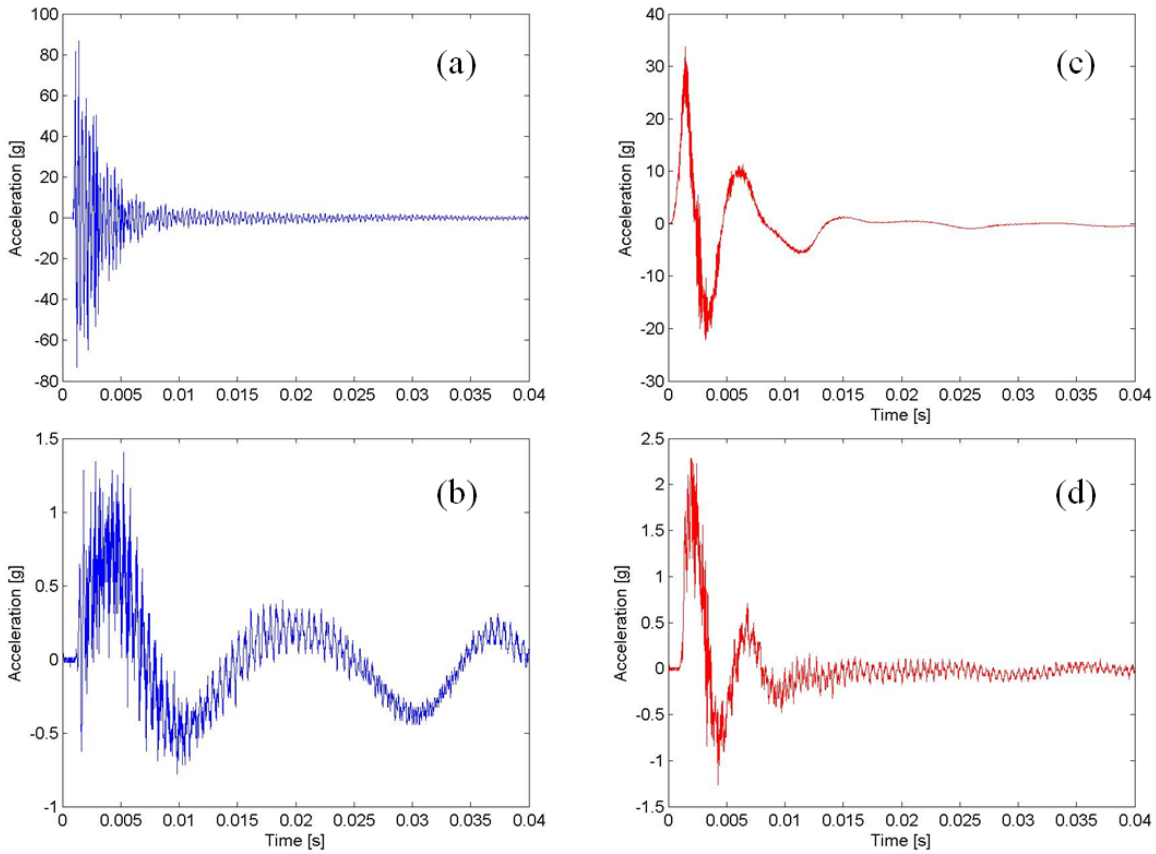

Figure 5. Shock accelerations measurements resulting from impact with different hammer tip: aluminium (a)(b) and rubber (c)(d), for the accelerometer mounted on the support plate and the shock transmission on the mass dummy (a)(c), with the foam/STF shock absorber (b)(d)

4.2 Shock response spectrum

Comparative SRS of the setup with the different shock absorbers are presented in Figure 6 for two types of shock solicitations: impact with aluminium and rubber tip.

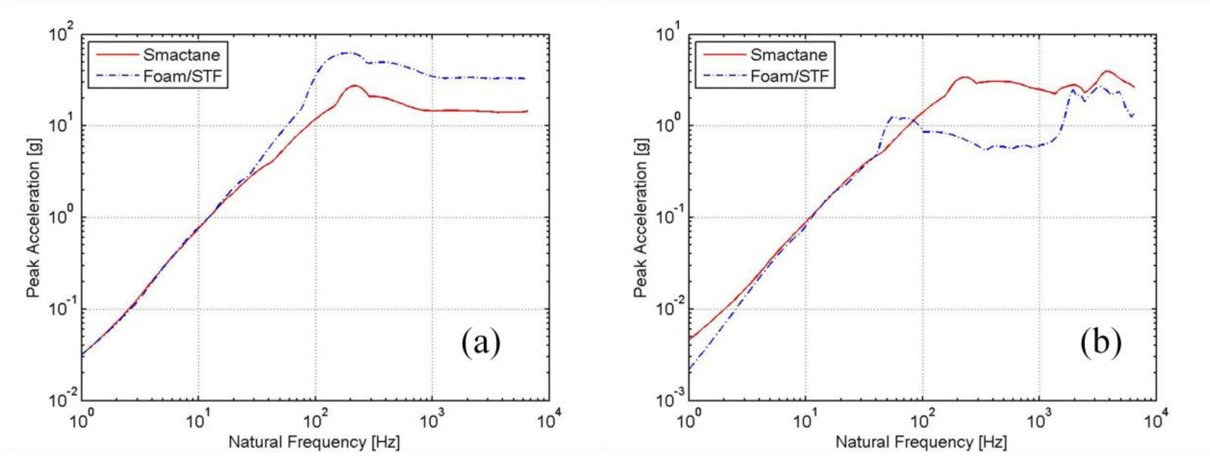

Figure 6. Comparative positive SRS of the two shock absorbers for impact using a hammer with an alu tip (a) or a rubber tip (b)

In view of the results, foam/STF shock absorbers offer better shock absorption properties than Smactane for an impact with the aluminium tip (Figure 6 (a)) especially on the range 100 to

1000 Hz. The response is opposite in the case of an impact with the rubber tip on the hammer (Figure 6 (b)). This is due to the absence of frequency higher than 100Hz on the shock impulse. Results for the plastic tip are consistent with the one with the aluminium tip.

5. Discussion and Conclusion

Shear Thickening Fluids are brought closer to practical applications in the case study presented in this work. This solution is very flexible as the foam shape is easily modifiable. Smart materials constituted of open cell foams impregnated with STF keep the intrinsic properties of a STF, which is the transition from a liquid to a solid state when submitted to a critical shear rate at a certain level of strain. The stiffness of the foam/STF composite increases with force amplitude and frequency. Shocks are local transient mechanical loading characterized by their short duration (µs to ms), high frequency (>100 Hz) and high instantaneous acceleration (>10 g) and high energy to dissipate. It might be speculated that shock solicitations trigger the transition from low to high viscosity.

In this case, the foam/STF shock absorber offers a better shock absorption than Smactane to shock with high energy, short impact duration and high frequencies component (plastic and aluminum tip). This response is consistent with the literature on impact response of STF [11]. Impact tests carried out in parallel show very good energy absorption during impact for foam impregnated with STF. The response to half sinus shock (rubber tip impact) is penalized by a low frequency oscillation of the mass dummy that do no shear the STF enough to activate it.

Even if the shock absorption properties of foam/STF is better for certain shock types, the low stiffness of foam/STF at rest and their complex processing made them less interesting than current elastomeric solution for the moment. But foam/STF is also efficient to provide damping for low frequencies/large deformations vibrations contrary to current damping material.

Future work is towards finding a design providing an enhanced stability and rigidity of the shock absorber to avoid oscillation at low frequency and testing at higher amplitude and frequencies. A silicone layer could be used to enhance stability. Also, STF are sensitive to humidity or to degassing. Then it is necessary to encapsulate the foam/STF in a material that protects it from evaporation of the solvent or water intake to preserve their shear thickening properties. Silicone has been proved to be an efficient encapsulation material.

Acknowledgements

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