Smart Viscous Dampers utilizing Shear Thickening Fluids with Silica Nanoparticles

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SUMMARY:
A significant number of researchers are convinced that the structural response could be reduced appropriately by installing damper devices. However, the damper deployed on buildings or bridges are generally designed only for the specific structural system under specific loading conditions. As a result, several researchers have developed the adjustable passive damper in recent years. Electro rheological dampers (ER dampers) and magneto rheological dampers (MR dampers) are well known adjustable damper systems, but the durability and the stability of the external power supply needed for ER and MR dampers are questionable for the long-term application during structure service life. Consequently, a new material, shear thickening fluids (STF), which changes its properties according to different loading rate without external power needed are considered to be a good filled material for innovative damper devices. In this paper it will be shown that applying STF materials on a conventional viscous damper device by using a simplified piston device and changing the concentration of STF filled can develop an innovative viscous damper which behaves like the MR damper. In this study, STF samples composed of three different sizes of silica nanoparticles (12, 16 and 40 nm) suspended in three types of solvent (polypropylene glycol, PPG) were fabricated in the laboratory. The shear properties of STF samples under the steady state and the oscillatory state were tested separately by using a rheometer. Furthermore, a prototype STF damper was developed and tested with preliminary performance experiments. Besides, hysteretic loops of the STF damper developed under various loading conditions were observed. The result shows the smart STF damper proposed in this paper might have a good potential in practical engineering applications.

Keywords: Fumed silica nanoparticle, Shear thickening/thinning fluid, Smart viscous damper

1. INTRODUCTION

It is well known that the structural response could be reduced appropriately by installing damper devices. However, the damper deployed on buildings or bridges are generally designed only for the specific structural system under specific loading conditions. As a result, several researchers have developed the adjustable passive damper in recent years [Wereley et al., 2004; Dimock et al. 2002]. Electro rheological dampers (ER dampers) and magneto rheological dampers (MR dampers) are well known adjustable damper systems, but the durability and the stability of the external power supply needed for MR and ER dampers are questionable for the long-term application during structure service life. Consequently, a new material, shear thickening fluids (STF), which changes its properties according to different loading rate without external power needed, is considered to be a good filling material for innovative damper devices [Zhang et al., 2008]. Lee et al. (2002) applied STF to develop the liquid body armor which is bullet proof with flexibility. Fisher et al. (2006) focused on the feasibility of integrating STFs into a composite sandwich structure which can lead simultaneously to changes in stiffness and damping under dynamic loading as the strain and/or frequency are varied.

This paper studies the feasibility of applying STF materials on a conventional viscous damper device by using a simplified piston device and changing the concentration of STF filled to develop an innovative passive damper which behaves like the MR damper. In this study, STF samples which were composed of nanosize fumed silica particles suspended in a solvent polypropylene glycol (PPG) were fabricated in the laboratory. The shear properties of STF samples under the steady state and the oscillatory state were tested separately by using a rheometer. Furthermore, a prototype STF damper was developed and tested with preliminary performance experiments. Besides, hysteretic loops of the STF damper developed under various loading conditions were observed. The result shows the feasibility of the STF damper proposed in this paper and indicates that it might have a good potential in practical engineering applications.

2. PRELIMINARY PERFORMANCE EXPERIMENTS

2.1. Preparation of STF Materials

This paper used the STF materials which contain three types of fumed silica nanoparticles, including: (1) OX50 with a primary spherical particle size 40 nm and a specific surface area approximately 50 m^2/g, (2) R972 with a primary spherical particle size of 16 nm and a specific surface area approximately 110 m^2/g and (3) R974 with a primary spherical particle size of 12 nm and a specific surface area approximately 170 m^2/g for performance experiments. The carrier fluid is polypropylene glycol ($H[OCH(CH_3)CH_2]_nOH$) with three different average molecular weight 400 g/mol, 1000 g/mol and 3000 g/mol (Fig. 2.1). In each of the experimental study cases, the carrier fluid was mixed with fumed silica particles by using a blender (Fig. 2.2) to mechanically stir the two components into uniform distribution. In order to get a good dispersion of STF fluid, the suspensions after the stirring procedure were conducted to pass three-roll mill six times. A three-roll mill is a mechanical tool that utilizes the shear force created by three horizontally positioned rolls rotating in opposite directions and at different speeds relative to each other to mix, refine, disperse, or homogenize viscous materials fed into it. Finally, the fully mixed STFs were placed in a vacuum chamber to eliminate bubbles inside the STF. The concentrations of the STF conducted in this study are 7.5%, 10%, and 12.5 %w/w.

Figure 2.1. Carrier fluids and nanoparticles

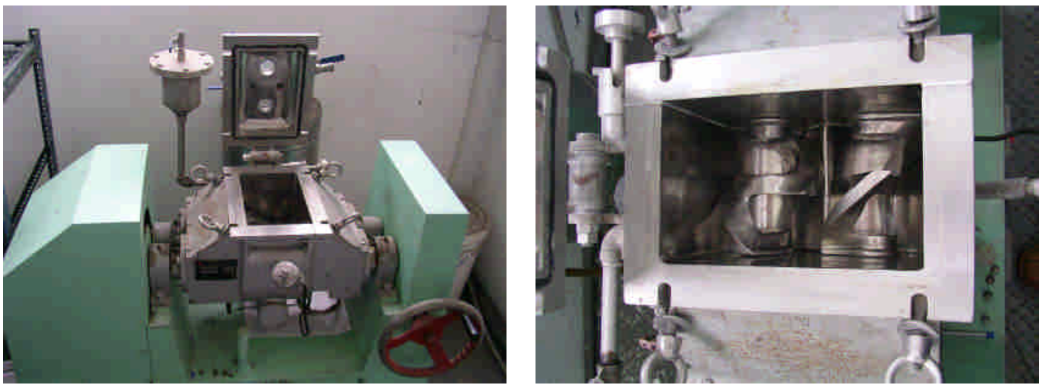


Figure 2.2. Blender for dispersion of STF fluid

2.2. Rheological Tests and Results

As for rheological property tests, rheological measurements were performed on a stress-controlled Rheometrics Scientific AR2000ex rheometer (Fig. 2.3a). Varied dynamic frequency tests were conducted by using a 40 mm diameter cone-plate tool (Fig. 2.3b) with a cone angle of 4 degree and a gap of 0.4 mm between the plate and the twitter. Figure 2.4 shows the experimental result of relationship between the viscosity and the shear rate of the carrier fluid applied under steady state. It shows that the polypropylene glycol matrix is a Newtonian fluid whose viscosity keeps at constant value under different shear rate.

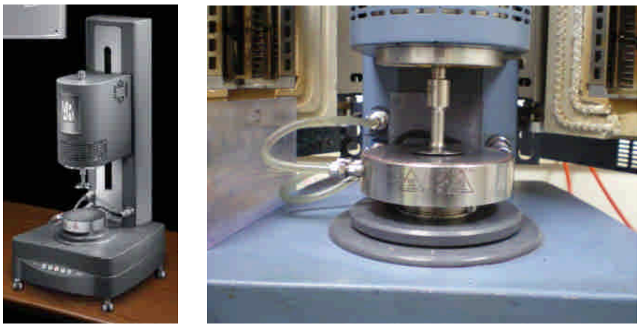


Figure 2.3. (a) Rheometer, (b) Cone and plate

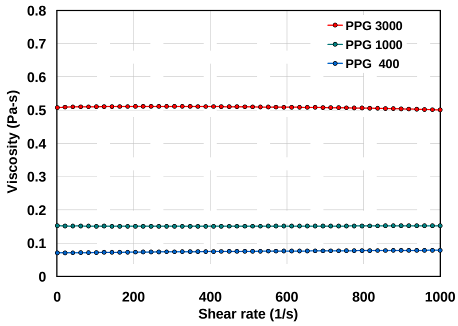


Figure 2.4. Viscosity as a function of shear rate for PPG

Figure 2.5 shows the experimental result of the relationship between the dynamic viscosity and the shear rate of STF material applied under 10% concentrations with R972 nanoparticles. The results show that STF fluids have high nonlinear behavior, and perform from low to high amplitude strains at different shear angular frequencies of 20, 40, 60, 80 and 100 rad s^{-1}, respectively. The STF exhibits strain thickening at high strain amplitudes, with its complex viscosity showing an abrupt jump to higher levels at particular strains for different shear frequencies. The data in behavior occurs at smaller strains as the frequency of the deformation is increased.

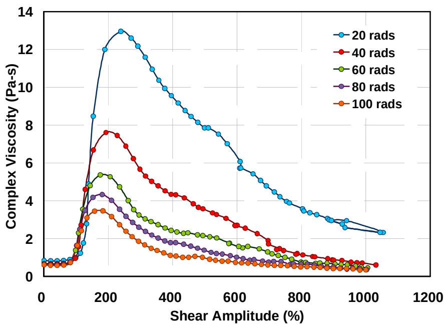


Figure 2.5. Dynamic strain sweeps at different angular frequencies for 10% (w/w) STF

According to the experimental data, Figure 2.6 gives the response of the 10% (w/w) STF for a critical shear strain γ_c and the strain at the end of the transition γ_m as a function of angular frequency ω. This figure could be used to predict whether the STF was in the low viscosity state, in the transition state or in the shear thickened state.

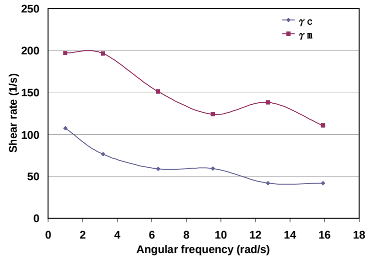


Figure 2.6. γ_c and γ_m as a function of angular frequency

3. PARAMETRIC STUDY ON RHEOLOGY OF STF

In this paper, the STF materials which contain three types of fumed silica nanoparticles (OX50, R972 and R974) and three different average molecular weight (400 g/mol, 1000 g/mol and 3000 g/mol) of carrier fluid PPG for parametric study. The concentrations of the STF conducted in this study are 7.5%, 10%, and 12.5 %w/w.

The results of parametric study are shown in Fig. 3.1 to Fig. 3.3. Figure 3.1 shows the rheological curve of 10% w/w STF for different carrier fluids with R974 nanoparticles. The results show that the viscosity of STF and amplitude of shear thickening increase as the molecular weight of carrier fluid increases. Figure 3.2 shows the rheological curve of 12.5% w/w STF for different fumed silica nanoparticles combined with 400 g/mol PPG carrier fluid. The results show that the viscosity of STF and amplitude of shear thickening increase as the specific surface area of nanoparticle increases. Figure 3.3 shows the rheological curve of different concentrations of STF with R974 nanoparticles in 3000 g/mol PPG carrier fluid. The results show that the viscosity of STF and amplitude of shear thickening increase as the concentration of STF increases.

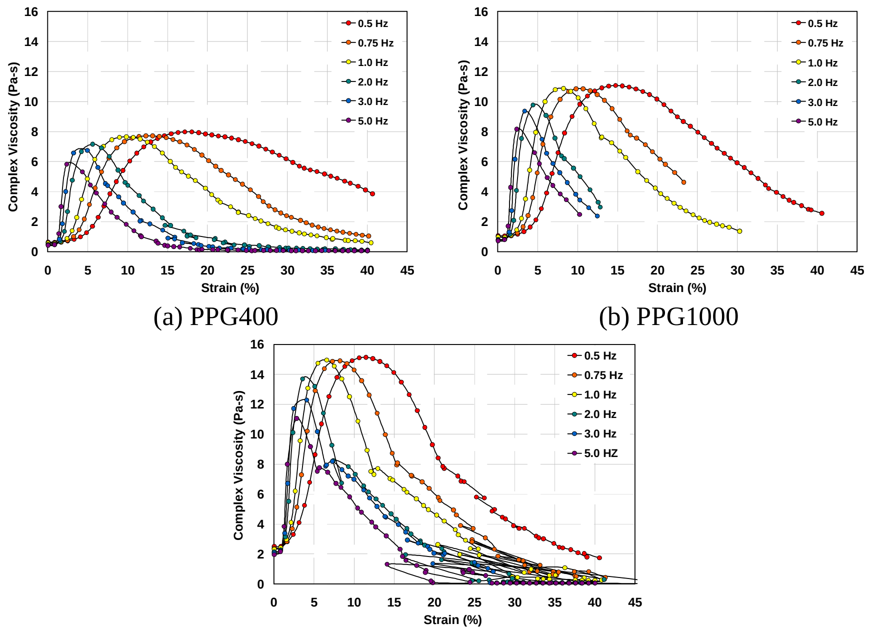
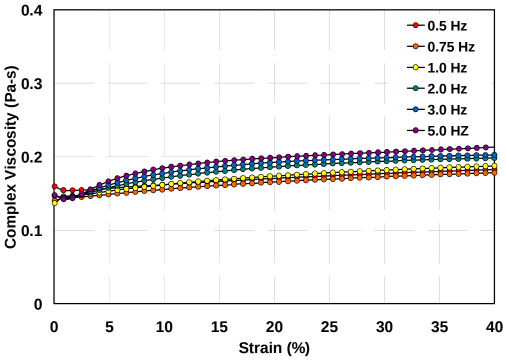
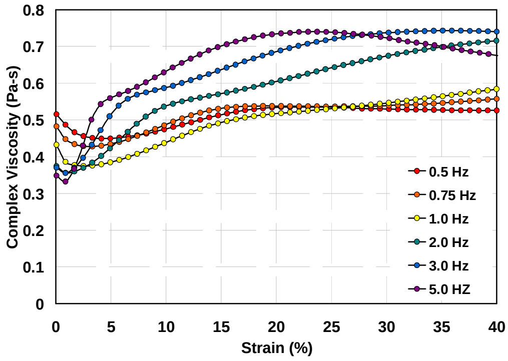


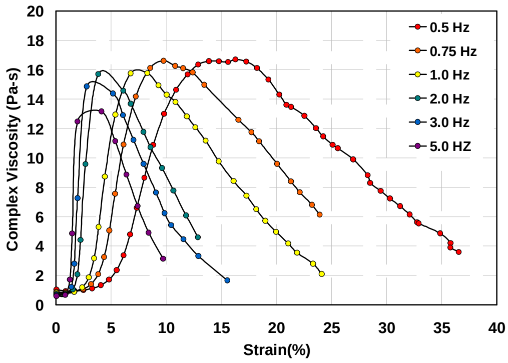
Figure 3.1. Rheological curve of STF for different carrier fluids (10% w/w STF with R974 nanoparticles)



(a) OX50

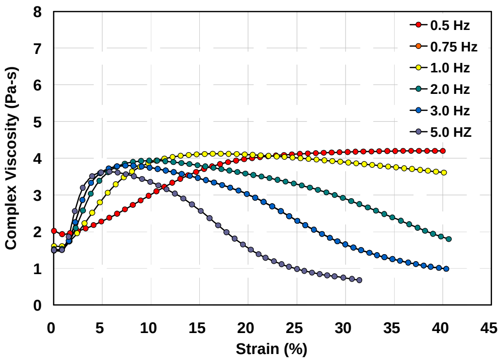


(b) R972

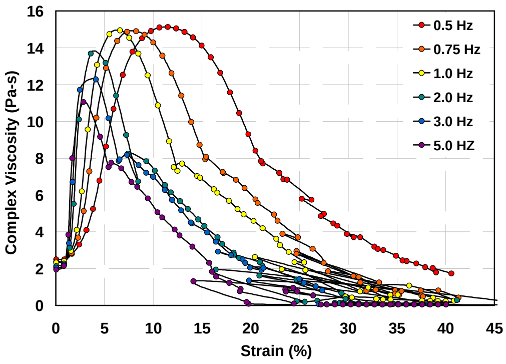


(c) R974

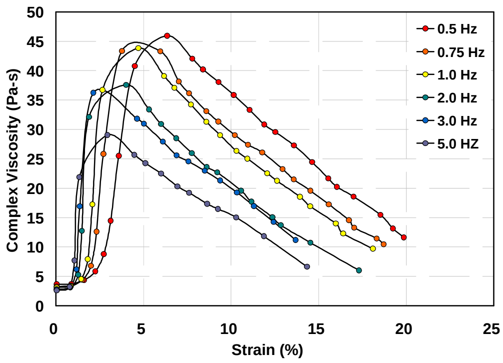
Figure 3.2. Rheological curve of STF for different nanoparticles (400 g/mol PPG and 12.5% w/w STF)



(a) 7.5%



(b) 10%



(c) 12.5%

Figure 3.3. Rheological curve of STF for different concentration STFs (3000 g/mol PPG with R974 nanoparticles)

4. PERFORMANCE TEST OF STF DAMPER

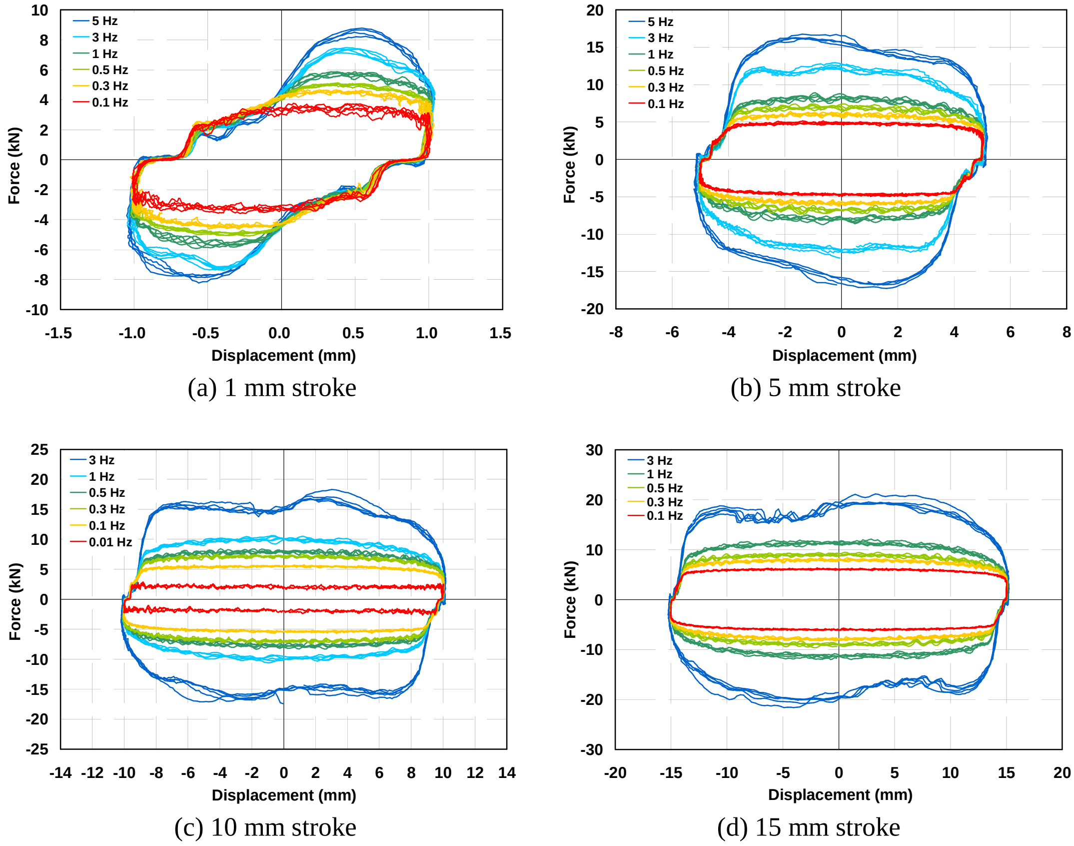
The mechanism of STF damper developed is similar to a conventional single-tube damper which consists of a piston, one flow tunnel and a cylinder. It consists of 4 parts elements including cylinder, piston head, oil seal and fluid. The photo of experimental layout of dynamic performance tests is shown in Fig. 4.1.

Figure 4.1. Layout of STF damper performance test

In this paper, the 10% w/w STF damper was tested under two conditions of harmonic excitation. Firstly with different frequencies at fixed stoke, the range of test frequency is from 0.1 Hz, 0.3 Hz, 0.5 Hz, 1 Hz, to 3 Hz according with the constant stroke of 1 mm, 5 mm, 10 mm, and 15 mm, respectively. Secondly with different stokes at fixed frequency, the range of test stroke is from 1 mm, 5 mm, 10 mm, to 15 mm according with the constant frequency of 0.1 Hz, 0.3 Hz, 1 Hz, and 3 Hz, respectively.

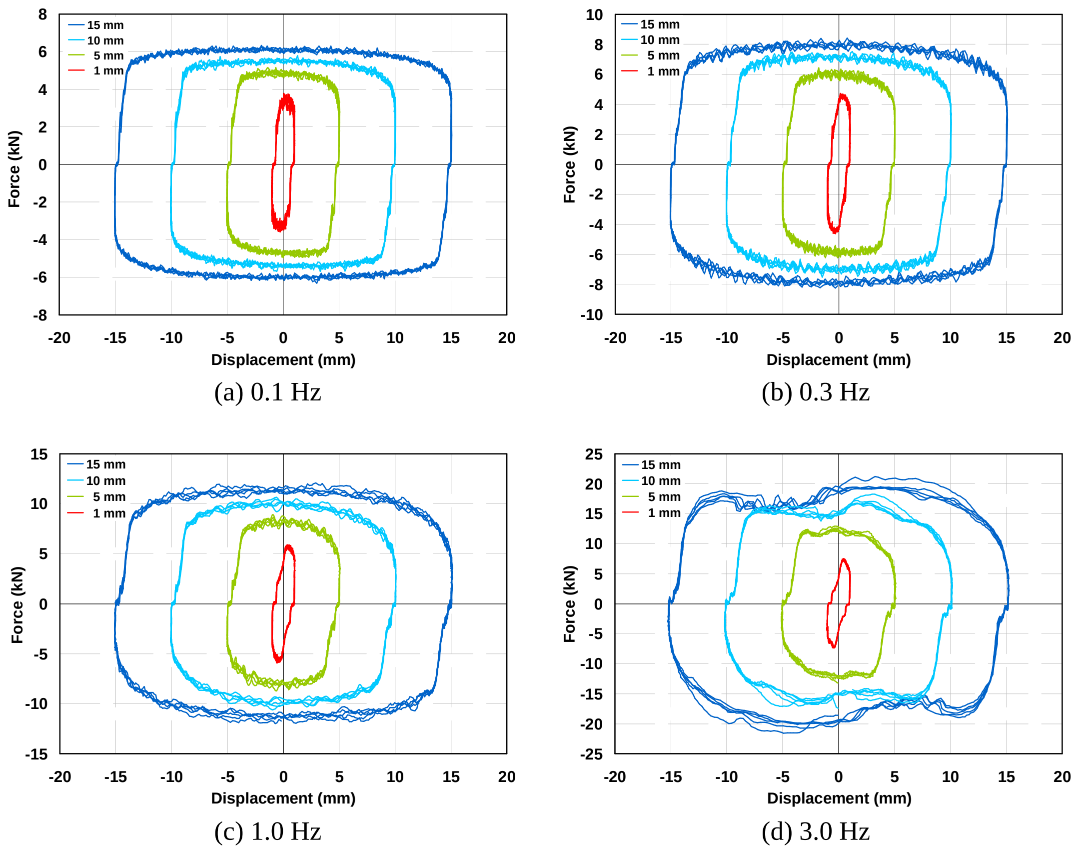
The experimental results in terms of damping force versus displacement at different frequencies are shown in Fig. 4.2 and Fig. 4.3. For each test, 6 cycles were repeated, and average values were taken to obtain the stabilized hysteresis loops. As can be seen from Fig. 4.2 and Fig. 4.3, the shape of the displacement damping force loop is strongly dependent on the loading frequency. For example, the peak damping force shows an increasing trend with frequency. In the low frequency range, such as 1 Hz, the STF presents a Newtonian fluid character. The area of the hysteretic loop per cycle denotes the energy dissipation capability. As the excitation frequency increases, the slope of the low velocity hysteresis loop increases. The damper works in the low viscosity state, in the transition state and in the shear thickened state when the excitation frequency is at 3 and 5 Hz, respectively. The hysteresis loop changes significantly as the excitation frequency passes 1 Hz.

Furthermore, the results of performance test under various excitation frequencies and strokes are shown in table 4.1 and table 4.2, it is clear that the STF-filled damper device has varied kind of damping coefficient with different loading frequencies. Figure 4.4 shows the force and velocity relationship of 10% w/w STF damper with R972 nanoparticles. The STF damper presents a nonlinear damper character under different loading frequencies. By applying such behavior characteristic, the developed device might be used for structural semi-passive control applications under different loading criteria. As a result, the preliminary experiment has proved the feasibility of STF-filled damper device.



(a) 1 mm stroke
(b) 5 mm stroke
(c) 10 mm stroke
(d) 15 mm stroke

Figure 4.2. Hysteretic loop of 10% (w/w) STF damper (Frequencies 0.1 Hz ~ 3 Hz)



(a) 0.1 Hz
(b) 0.3 Hz
(c) 1.0 Hz
(d) 3.0 Hz

Figure 4.3. Hysteretic loop of 10% (w/w) STF damper (1 mm~5 mm stroke)

Table 4.1. Damping coefficient and index of 10% (w/w) STF damper under various excitation frequencies

Stroke (mm)	Frequency (Hz)	Maximum force (kN)	Damping coefficient (kN s/mm) C	Damping index (α)
10	0.1	5.738	3.857	0.187
10	0.3	7.484	3.603	0.228
10	1.0	10.627	0.870	0.598
10	3.0	16.289	1.266	0.494

Table 4.2. Damping coefficient and index of 10% (w/w) STF damper under various strokes

Stroke (mm)	Frequency (Hz)	Maximum force (kN)	Damping coefficient (kN s/mm) C	Damping index (α)
1	3.0	4.546	4.555	0.136
5	3.0	13.199	1.161	0.591
10	3.0	16.289	1.266	0.494
15	3.0	18.597	1.118	0.521

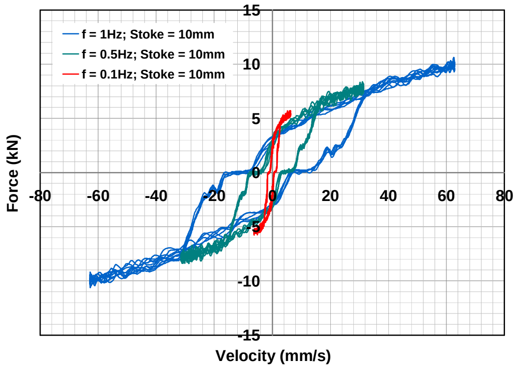


Figure 4.4. Force vs. velocity of 10% (w/w) STF damper filled with R972 nanoparticles

5. SUMMARY AND DISCUSSION

This study has indicated that the STF material, which is composed of nanosize fumed silica particles suspended in a solvent, can be used as damping elements to fill in the viscous damper device. Preliminary experimental test results have shown that the STF damper developed can lead simultaneously to changes in damping under dynamic loading with varied frequencies or stroke. The result also points that the velocity of dynamic loading has a significant influence on the fluid viscous properties, which has a large influence on the energy absorption response during the working of the damper. And it can be said that STF damper could be considered as an innovative passive damper device for structural applications in the future.

Moreover, there are few topics which will be further studied in the future. Firstly, the settlement of fumed silica particle in STF, if the Brownian movement of nanoparticles is larger than itself in weight, the probability of settlement is quite rare. In order to study this phenomenon, the STF fluid will be placed for six months and the rheological properties will be compared with new-made STF. Secondly, in order to develop a design method of STF damper for engineering application, it is important to build the database of STF fluid and to simulate the dynamics behavior STF-filled traditional viscous damper. It can be predicted the STF-filled traditional viscous damper performance by CFD program.

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