Application of Shear Thickening Non-Newtonian Fluid to Minimize Head and Neck Injury

Jose Herrera
Vaughn College of Aeronautics and Technology, Flushing, NY, USA, jose.herrera@vaughn.edu

Mamunur Anik
Vaughn College of Aeronautics and Technology, Flushing, NY, USA, mamunur.anik@vaughn.edu

Faculty Mentors:
Dr. Amir Elzawawy
Vaughn College of Aeronautics and Technology, Flushing, NY, USA, amir.elzawawy@vaughn.edu

Dr. Yougashwar Budhoo
Vaughn College of Aeronautics and Technology, Flushing, NY, USA, yougashwar.budhoo@vaughn.edu

ABSTRACT

In this project, the application of shear thickening non-Newtonian fluid is proposed to dampen sudden acceleration and deceleration to minimizing neck trauma also known as "whiplash". The shear-thickening characteristics in some non-fluids are being exploited to provide substantial non-linear damping to sudden acceleration that happens in some sports accidents such as in car racing. The experiments are conducted using a mixture of cornstarch (55 %) and water (45%). Initial experiments demonstrated strong shear thickening behavior at high shear rate (du/dy), which is relevant to high acceleration that occurs in the time of the accident. The shear thickening fluid also demonstrates low shear stress behavior at low shear rates. This also is desirable to provide smooth neck motion. A simple device was constructed to demonstrate and test the concept of using shear damping fluid, consisting of a clear PVC reinforced hose, fixed at one end, then filled with the cornstarch solution and a free floating chain is placed inside the hose. The cornstarch solution surrounds the chain; the chain links in conjunction with the inner wall surface of the flexible hose provide the friction needed to induce a shear force. The result is a damping characteristic caused by the high shear stress of the fluid.

Keywords: Non-Newtonian, Shear thickening fluid, Damping, and Robustness

1. INTRODUCTION

One of the most common injuries associated in sports and vehicle accidents involves neck injuries. As an indication of the size of the problem in-hand in 2007, the costs of neck injury claims to insurance companies were estimated to be about $8.8 billion dollars [1]. In the attempt to reduce neck injuries, this project is based on using the shear-thickening characteristic of a non-Newtonian fluid and applying its effects in reducing neck injuries. Helmets and different versions of spinal protection are used to minimize head and spinal injuries; however, the neck region remains vulnerable. A proposed solution is to bridge the gap between the head and shoulders for continuous protection of the spine. Currently, the vulnerable neck is protected with bulky neck collars, used to dampen the effects of whiplash; thus, reducing neck mobility.

1.1 BACKGROUND

A non-Newtonian Fluid has a unique characteristic; it exhibits both properties of liquid and solid, as the relationship between the shear stress and the shear rate becomes non-linear as shown in figure 1. This characteristic has been known and studied for some time and has been applied to consumer products and military use. For example, Shear-thickening fluids are currently being utilized in a number of commercial applications including use in “machine mounts, damping devices, and limited slip differentials” [7]. The Hughes Aircraft Company [2] developed a viscous fluid damper utilizing the unique characteristics of Non-Newtonian fluids. Non-Newtonian fluids are usually very dense, but their one ability is to form itself into a solid momentarily when an external force impacts the fluid as it produces high shearing rate. The harder the impact, stronger the liquid becomes to resist the impact. When no force is acting, the non-Newtonian fluid is gloppy. To illustrate the versatility of this concept further, currently the U.S. Army, along with the University of Delaware at Aberdeen Proving Grounds, is testing and developing liquid body armor as a means to slow down the impact of any high-speed projectile based on the same concept [3].

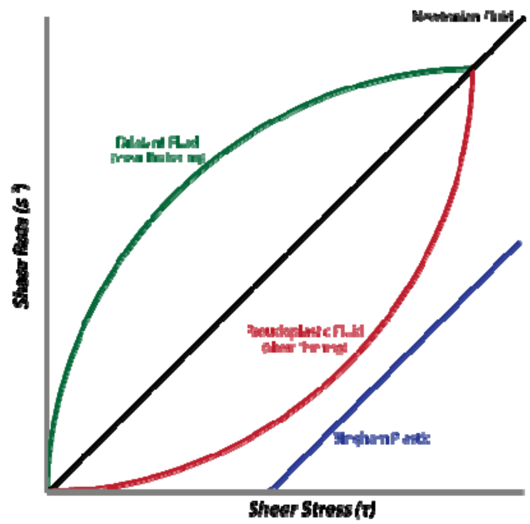

Figure 1: The relation between the shear straa and the shear rate for Newtonian and Non-Newtonian Fluids

There are many non-Newtonian fluid categories, in this project the cornstarch solution is selected for its economical and availability. This mixture is categorized as a dilatant or shear thickening fluid. It has a direct proportional relationship between viscosity and shear rate. As shear rate increases, viscosity also increases and is graphically shown in figure 2.

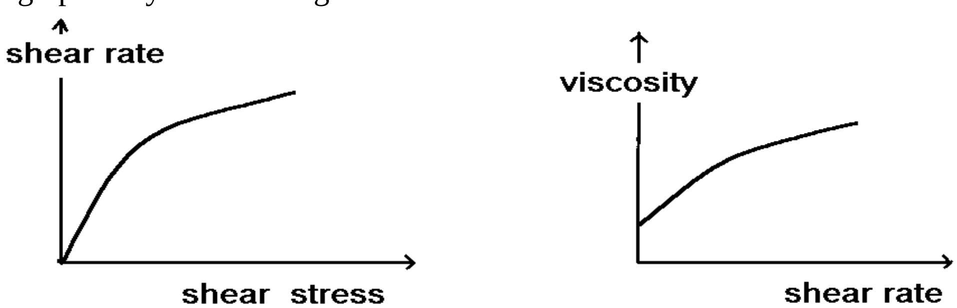

Figure 2: Shear thickening behavior

Many studies have been done on the subject of shear thickening, allowing for different sources to be used to gather the information needed for this particular subject. For example, a graph based on past research done by University of Massachusetts [7], illustrated in figure 9, and was helpful in defining the shear thickening properties of the cornstarch mixture used for this project. For the purposes of this project, a small portion graph was used that fit the desired behavior. The area of interest is the region of the graph where viscosity increases due to an applied force, after the *5* s^{-1} *shear rate* is exceeded; this is when the fluids viscosity increases. What is observed in the graph is as the increasing shear rate causing a proportional increase in the fluids viscosity or shear thickening. The portion of interest was analyzed to find the best curve fit equation. Using Excel the equation obtained was a 6th order polynomial shown in figure 4, this equation will be helpful in adjusting the viscosity needed to optimize dampening effects of the shear thickening fluid.

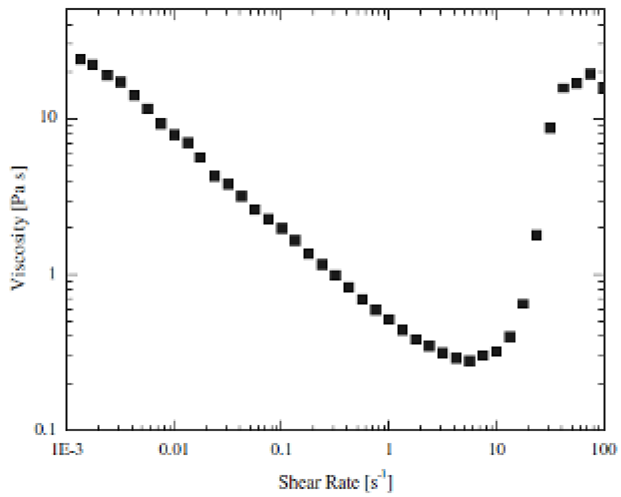

Figure 3: Steady-shear rheology of 55 wt. % cornstarch in water suspension

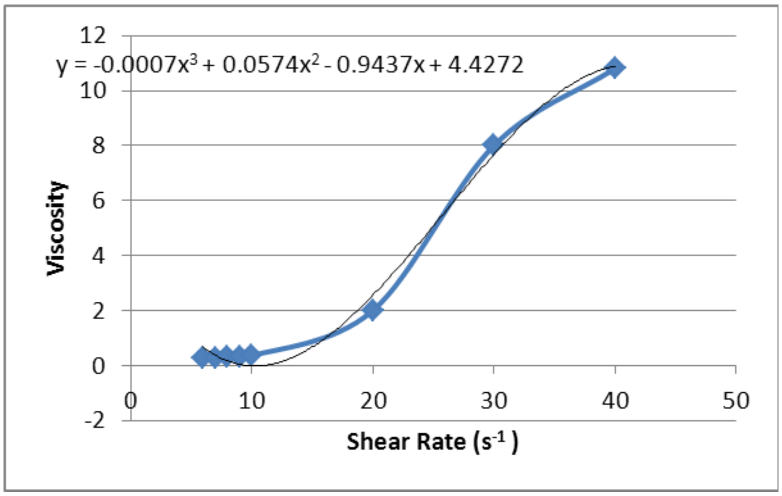

Figure 4: Curve fitting of portion with desired behavior

The viscous damping force created by the shear thickening fluid is difficult to find due to its non-linearity. An ideal model is assumed for the general equation of motion to find an approximation of the viscous damping force created by the shear thickening fluid; shown in equation 1. In this equation, the external and body forces are neglected; simplifying to equation 2 shown below.

$$m\ddot{x} + c\dot{x} + kx = \sum F \qquad \text{(Equation 1)}$$

$$m\ddot{x} + c\dot{x} = 0 \qquad \text{(Equation 2)}$$

From this point the damping force can be expressed as:

$$c\dot{x} = m\ddot{x} \qquad \text{(Equation 3)}$$

Since, the non-Newtonian fluids viscosity is a function of the velocity. The shear stress is expressed as:

$$\tau = \mu_{\left(\frac{du}{dy}\right)} \cdot \left(\frac{du}{dy}\right) \qquad \text{(Equation 4)}$$

The resistive force is:

$$F - \tau \cdot A \qquad \text{(Equation 5)}$$

By expressing F as:

$$F = c\dot{x} \qquad \text{(Equation 6)}$$

$$\tau \cdot A = c\dot{x} \qquad \text{(Equation 7)}$$

$$c = A_s \cdot f\left(\frac{du}{dy}\right) \cdot \left(\frac{\left(\frac{du}{dy}\right)}{\left(\frac{dv}{dt}\right)}\right) \qquad \text{(Equation 8)}$$

<u>where:</u>

τ: shear stress
μ: viscosity
m: mass
v: velocity
$\ddot{x}$: acceleration
$\dot{x}$: velocity
$x =$ displacement
k: spring constant

The equation 8 will be used as a starting point in determining the approximate viscous damping force as shear thickening fluid reactions to various loads. In future phases of this project, this equation may change as more sophisticated equipment and materials are used.

2. Design

Traditionally, vibrations and impacts are damped either by mechanical or electronic means; The present design uses the known characteristics of a shear thickening fluid in a controlled manner; this shear damping fluid device is simple and robust. The simplicity comes from using readily available materials and has very few moving parts, thereby; keep manufacturing and maintenance costs down. The device proposed here meant to have an automatic actuation as it works instantly when it experiences a shearing force. The shearing action can be adapted to various geometries and configurations depending on the end result being achieved. The main objective is to develop a working model, which will act as spinal protection in a frontal automotive collision. Refer to figure 5 for a visual understanding of the equipment used. The prototype device will be attached to the back of the helmet and the spine protector along the length of the spine as shown in figure 6. Since, the non-Newtonian fluid behaves like a Newtonian fluid when no force or acceleration is experienced; the neck moves in its natural range of motion. The hose is filled with the shear thickening fluid, which is a mixture of cornstarch and water and the hose is fixed; the hose ends are closed both to prevent fluid spillage. To activate the shear thickening fluid a sudden longitudinal shearing force is applied to the chain. The fluid medium provides a consistent contact between the inner wall surface of the hose and chain link surface areas; also the chain provides additional friction. A high shear rate and acceleration occurs as the weight of the head and helmet starts to rotate forward; in this experiment a 15 lbs. weight substitutes for the head and helmet. The forward motion or flexion of the head causes the opposing surfaces between inner wall surface of the hose and chain links surface areas to slide past each other. The sudden motion induces the necessary shear thickening and strain hardening to slow down the acceleration. An important relationship that is of interest is in how the fluids viscosity increases due to shear rate or velocity. This unique property will be used in a manner to reach the objective of providing a means to minimize neck trauma.

Figure 5: a) Clear tube, b) Chain, c) corn starch mixture

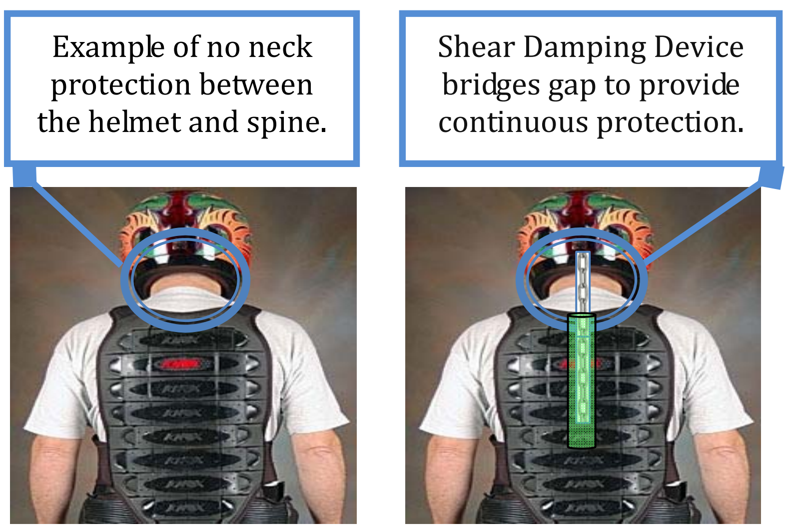

Figure 6: Illustration of unprotected and protected neck

3. Application

The prototype shear damping fluid device, so far, is expected to reduce neck injury in tension as the head moves forward. For the second phase, the design needs to be modified in a way that allows the shear thickening fluid to be activated as the head moves backward known as extension. The third design phase, will allow protection for the neck from a lateral collision, which is even more complicated. Presently, there is not a specific design for this particular situation, however; with sufficient time, it will be worth trying to modify the design to satisfy the requirements mentioned. Thus, helping drivers and athletes extra protection from neck injury. Even though, this particular model has a very specific goal there are other areas where the usage of non-Newtonian fluids can be helpful to the society. Depending on the materials, ingredients and mixture ratio, the non-Newtonian fluid can be woven into fabrics such as ropes, safety harnesses, seatbelts and in combination with shock absorbers to assist in further damping effects.

4. Experiments

In the first experiment, the shear damping fluid device was subject to a drop-test, shown in figure 7. The reinforced PVC hose had one end closed with an eyebolt, which served two purposes; this allowed an attachment point for the 15 lbs. weight and prevented the fluid from leaking out. One end of the chain was fixed and suspended on a cross member. The cross member was supported by two tripod stands. The chain was then placed inside the open end of the reinforced PVC hose and the shear thickening fluid was poured inside the hose. The overall idea is to use digital camera to video the drop test by allowing the weighted hose to fall freely and observe how well the shear thickening fluid resisted the motion. The device was only subjected to a 1g, equal to 9.8 m/s^2. From the video, data such as distance, velocity, and acceleration are obtained using Imotion tracking application . After the data was collected and analyzed, it was noted that the acceleration was not constant; therefore, making initial kinematic calculations difficult to solve. In a car frontal collision shown in figure 12, a driver's head experiences more than 1g or about 140 ft-lbs of force [6], show in table 1, and the forces involved depend on many factors that include the speed of the car at the time of impact. To achieve more than 1 g, the velocity needed to be increased; with the increased velocity the shear damping fluid device needs to withstand and keep the head and neck from exceeding a rotational force of about 140 ft-lbs or less to minimize injury. An idealized mathematical model was created to simulate the spine and weight of the head in frontal impact collision. A crude representation of the idealized model is illustrated in figure 9. The shear damping device in the mechanical system is represented by *dash- pot damper* in the illustration and by the *damping coefficient* in the mathematical equation. Analytically, this allows the mathematical model to be adaptive in observing how effective the damping force and displacement caused by the *shear damping device*, at different velocities, would affect the neck to be within the allowable limits before injury occurs. A testing apparatus was fabricated, shown in figure 10, to simulate the spine and weight of the head; and to test shear thickening damping effects of the prototype device in frontal impact collision. For safety reasons and time constraints, three tension springs in a *parallel configuration* were used to provide the velocity necessary to provide sufficient tensional force. A high velocity can be gained from spring's potential energy. The prototype device is attached to a hinged lever arm, in such a way that when the lever is released the rotational motion will produce a sufficient velocity to activate the fluids resistance. The testing apparatus was built using various items, such as, tensional springs bought at a hardware store, a tow bar, turnbuckle and hex dumbbell for different weights; for safety and consistency a simple gate lock with a cable lanyard is used as a trigger mechanism. To collect the data, a video camera and an Apple iPhone were used along with motion tracking software called "Tracker". The motion tracking software was a great tool that allowed for reasonable video analysis in a timely manner. A plot shown in figure 11 is created using the values collected from the motion tracking software and inputted into an Excel spreadsheet. From this preliminary test with 5 lbs., the longest line represents, the predictable motion of the angular acceleration as the test apparatus is released without the shear damping device as it rotates. The shortest line represents rotation of the test apparatus with the shear damping device installed. As the test apparatus is in motion, the shear damping device instantly activates. This graph dramatically illustrates the dampening effects of the angular acceleration caused by the shear damping device.

Figure 7: Stand, weighted bag and measuring tools used to suspend and test prototype device

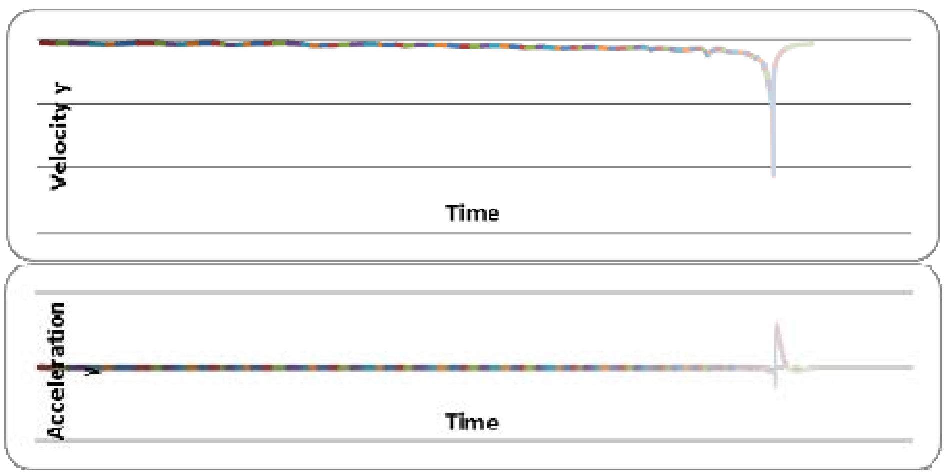

Figure 8: graphical results of 15 lbs. drop test

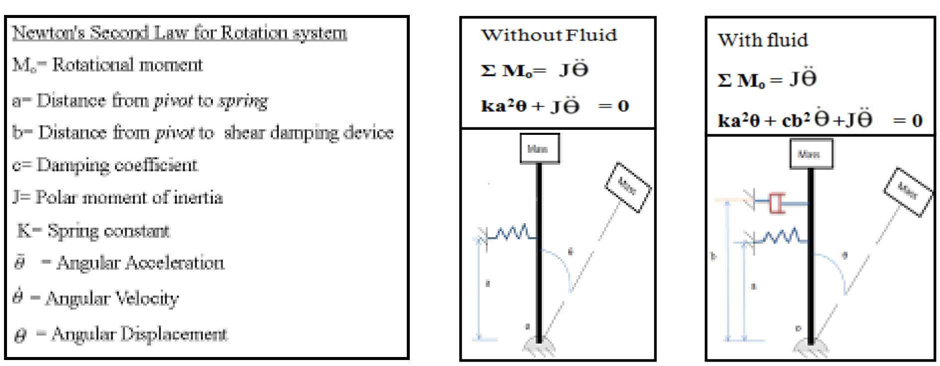

Figure 9: Experiment 2: Idealized spine and head mass model

Figure 10: Physical experiment of idealized spine and head mass model

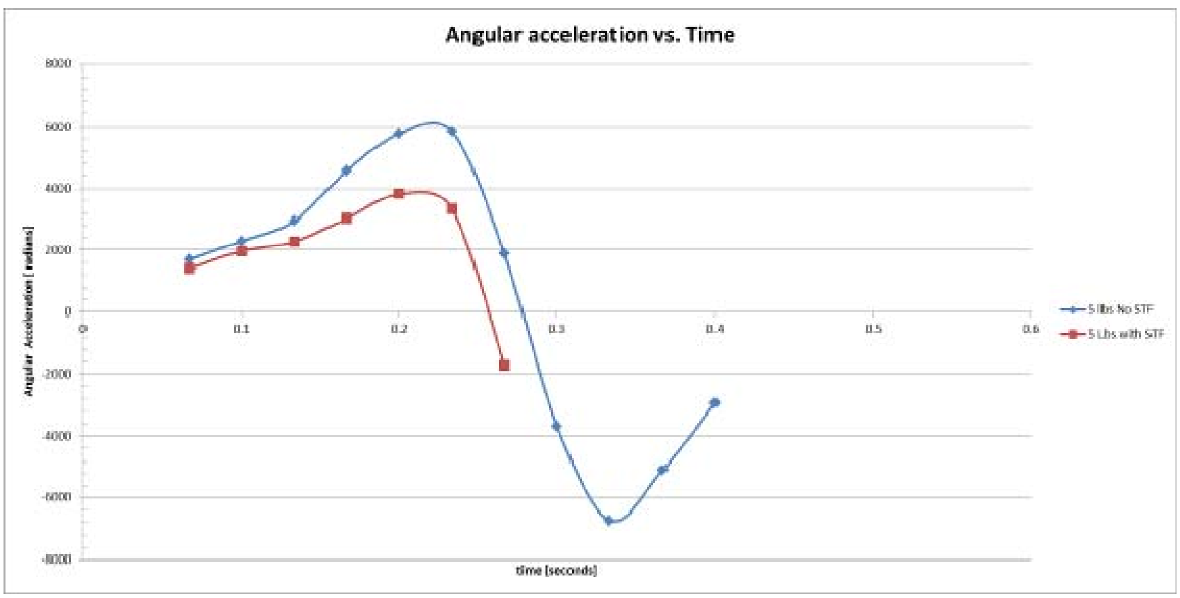

Figure 11: Physical experiment of idealized spine and head without and with the shear damping device

Table 1: Allowable neck limits before damage occurs

Loading	Allowable	
Axial compression	4000 N	900 lbs.
Axial tension	3300 N	742 lbs.
Fore and aft shear	3100 N	697 lbs.
Flexion bending moment	190 Nm	140 ft-lbs.
Extension bending moment	57 Nm	42 ft-lbs.

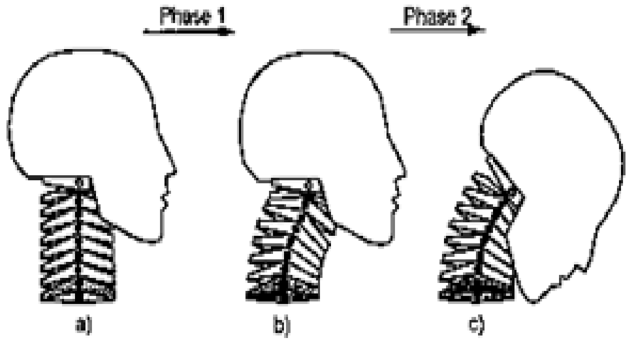

Figure 12: 1) Neutral position 2) Head translates forward 3) Head and neck rotate forward

In concept, consequent tests have shown promise that a shear thickening fluid can be applied into safety devices, such as the one being proposed in this paper, to aid in reducing neck trauma. The proposed shear damping device in combination with other safety equipment would increase a driver's survivability and recovery in a vehicular accident. To date, these experiments are being done with limited resources using rudimentary equipment and methods which have yielding surprising results. There were some obstacles faced during testing. The first is safety the testing apparatus constrained the experiments to low but reasonable velocities. Second, a high speed camera is needed to capture the test in more detail. Third, better testing equipment is required to asses accurately displacement, velocity and accelerations with the shear damping device. Fourth, the water would eventually separate from cornstarch mixture at a small period of time. The limitations encountered in the experiment were not a deterrent. In fact, the experimental process emphasized further the resilience, simplicity and robustness of shear damping device in very spartan conditions. As the values are being quantified, the next phases will need to be scaled up to simulate actual conditions encountered by individuals in collisions. Also a synthetic oil based shear thickening fluid will be used.

5. Conclusion

The proposed device is meant to use the shear-thickening material properties of a non-Newtonian fluid to damp the forces generated on the neck joints in sports accidents due to the sudden increase of the acceleration of the head relative to the main body which is constrainted by the safety belt. The intial experiments showed high damping effect produced by the device proposed at high acceleration rates and low shear stress at low acceleration. Both cases are desirable as explained above. To determine the damping effects of the shear thickening fluid damping device the overall performance of the tests will be scaled up to account for higher deceleration rates to understand the device damping characteristics at higher shear rate. This will be important to move to the optimizatizing stage the proposed shear damping device.

REFERENCES

[1] *Q&a: Neck injury*. (2013, January). Retrieved from http://www.iihs.org/research/qanda/neck_injury.aspx

[2] Hughes Aircraft Company (Culver City, CA) (09/23/1975). Retrieved from website http://www.freepatentsonline.com/3907079.html

[3] Global Security. February 18, 2010.

http://www.globalsecurity.org/military/systems/ground/body-armor3.htm

[4] Inglis-Arkell, E. (2010, December 20). *io9.com*. Retrieved from http://io9.com/5715076/non newtonian-fluids-the-weirdest-liquids-youve-ever-seen

[5] "Rheology Measurements." N.p., n.d. Web. 13 Mar. 2013. http://people.sju.edu/~phabdas/physics/rheo.html.

[6] Sanfelipo, T. (2011). *Understanding head and neck trauma*. Retrieved from http://www.bikersrights.com/statistics/trauma.html

[7] White, E. E. B., Chellamuthu, M., & Rothstein, J. P. (2010). Extensional rheology of a shear-thickening cornstarch and water suspension. Rheologica acta, 49(2), 119-129.

Authorization and Disclaimer