Analysis of Hydraulic Power Transduction in Regenerative Rotary Shock Absorbers as Function of Working Fluid Kinematic Viscosity

BY

Shakeel N. Avadhany

S.B. Materials Science & Engineering
Massachusetts Institute of Technology, 2009

SUBMITTED TO THE DEPARTMENT OF MATERIALS SCIENCE & ENGINEERING IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF

BACHELOR OF SCIENCE IN MATERIALS SCIENCE & ENGINEERING AT THE MASSACHUSETTS INSTITUTE OF TECHNOLOGY
[June 2009]
MAY 2009

Signature of Author: ______
Department of Materials Science & Engineering
May 14th, 2009

Certified by: ______________________
Caroline Ross
Professor of Materials Science & Engineering
Thesis Supervisor

Accepted by: ______________________
Lionel Kimerling
Professor of Materials Science & Engineering
Chairman, Undergraduate Thesis Committee

Contents

ABSTRACT

This investigation seeks to investigate the relationship of kinematic fluid viscosity to the effective power transduction seen by a hydraulic motor. Applications of this research specifically relate to energy recovery from a vehicle suspension system through the shock absorbers. A regenerative, hydraulic-based, rotary shock absorber was designed and fabricated for the purposes of this investigation. The kinematic viscosities ranging from 100 cSt to 200 cSt were used in the fluid circuit and tested for maximal efficiency of the hydraulic system. Balance between shear-force losses in the fluid circuit, and effective transfer of momentum at the water-wheel type hydraulic motor demonstrates that optimized performance of the system is attained when a midpoint is reached in the kinematic viscosity of the fluid.

INTRODUCTION

It is known that automobiles are inefficient, wasting over 80% of the energy stored in the fuel as heat. Thus eight of every ten gallons in the vehicle's tank don't help propel the vehicle; they are burned to overcome losses in the system.

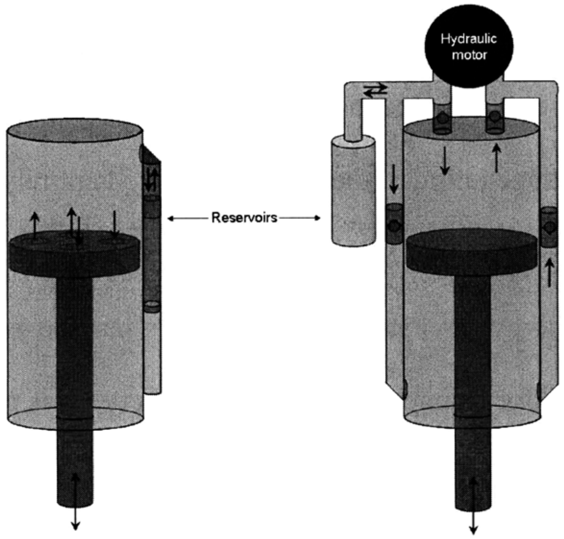
Automobile manufacturers have made costly strides to improve fuel economy. For example, regenerative braking is standard on many hybrid automobiles. Car manufacturers also spend a great deal of effort to reduce wind drag so as to improve fuel economy through streamlined, low drag automobile body designs. Manufacturers also use lighter, yet more expensive, materials to reduce vehicle weight to reduce fuel consumption.

Motor vehicles include a suspension system to control vertical motion of the wheel with respect to the vehicle. In addition to springs, shock absorbers are provided to provide damping. The energy removed from a conventional suspension system is lost as heat. There are known systems that attempt to recover suspension system energy. For example, U.S. Patent No. 7,261,171 teaches a mechanical arrangement in which reciprocating movements of a wheel relative to a vehicle body are converted to rotations of an armature of a generator to produce electricity for recharging the battery of the vehicle. Another electromechanical regenerative system is disclosed in U.S. Patent No. 5,570,286 that utilizes a magnet moving in relation to conductive coils.

This investigation looks into the most efficacious rotary hydraulic mechanism of harvesting energy from a vehicle suspension system. More specifically, it investigates the viscous nature of the working fluid in a rotary design regenerative shock for more effective power transduction. Custom apparatuses were fabricated for the purpose of this investigation. Both dynomometer and vehicle retrofit testing were performed to evaluate the results of electrical generation.

BACKGROUND

GenShock is a regenerative shock absorber developed by the Levant Power Corporation and is currently undergoing design changes to attain greatest efficiency. The system is the industry's first hydraulic rotary shock absorber, a device that converts vertical motion into rotary motion via a hydraulic motor.



Standard twin-tube shock absorbers use multi-stage fluid-restricting valves to damp the suspension and dissipate energy

GenShock uses a hydraulic motor, coupled with an electric generator, to provide damping and harvest the otherwise wasted energy

Figure 1: Standard shock juxtaposed to GenShock.

GenShock includes a piston disposed for reciprocating motion within a cylinder as a vehicle's suspension system deflects. Hydraulic fluid is contained within the cylinder. A first fluid circuit is in fluid communication with a first chamber in the cylinder on a first side of the piston, in fluid communication with an hydraulic motor and in fluid communication with a capacitive reservoir. Upon compression of the piston, hydraulic fluid passes through the hydraulic motor thereby turning a shaft thereof. A second fluid circuit is in fluid communication with a second chamber in the cylinder on a second side of the piston and also in fluid communication with the first chamber. Upon extension of the piston, hydraulic fluid passes from the second chamber to the first chamber. An electric generator is connected to the hydraulic motor shaft for generating electricity upon rotation of the shaft.

The device also includes a hydraulic circuit arrangement so that energy may be harvested during both compression or relaxation of the shock absorber. In this embodiment, upon compression or relaxation of the shock absorber, the resulting pressure differential across the hydraulic motor will induce rotational motion of its output shaft. This output shaft is directly connected to a permanent magnet generator/DC electric motor. The wattage rating of the motor is selected entirely based on the vehicle's mass and spring stiffness.

The electrical energy generated by the generator may be used by the vehicle as it is generated or stored in, for example, the vehicle's battery. It is preferred that the harvested electricity be used to power components on a vehicle that would otherwise strain the internal combustion engine, thereby increasing fuel efficiency.

Beyond the basic fluid losses in the hydraulic circuits, damping is provided mostly by the electric generator as the counter-EMF resists rotational motion of the armature relative to the stator. This resistance is transferred directly to the shock fluid by the hydraulic motor. The damping force provided by the motor is selected to be directly proportional to the velocity of the hydraulic fluid so that increased fluid velocity results in an increased damping force. GenShock leverages the counter-EMF of the electric generator (permanent magnet) to provide damping as a function of velocity. As shown in FIGURE, the RPMs of the electric motor are linearly correlated to the resistive torque seen at the shaft end due to the counter-EMF.

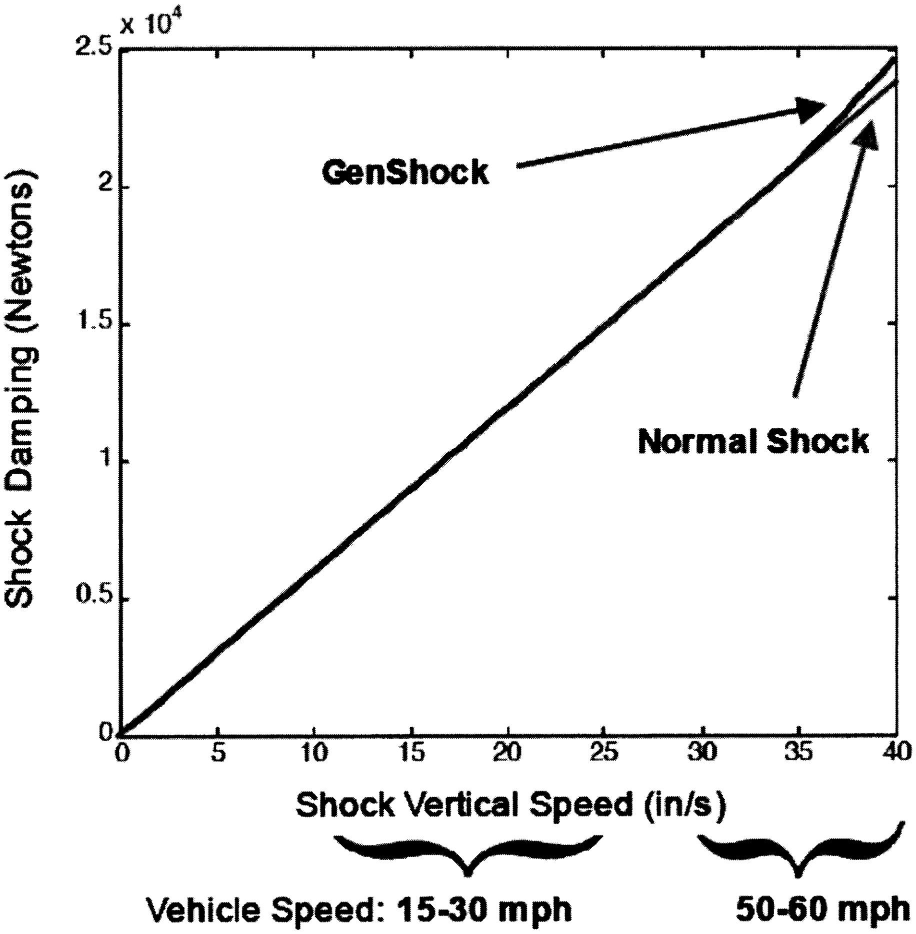


Figure 2: Demonstration of the damping capabilities of GenShock vs. a conventional shock.

The capacitive reservoir accommodates the piston shaft volume that is introduced upon the compression stroke of the shock absorber of the invention.

Some of the theory on which this investigation is based will be discussed. It is important to note how much energy is typically lost in the vertical motion of a car or truck so as to be able to decide whether the energy is worth harvesting. The model chosen to use is a simple spring-based model in which the energy that is present in the vertical motion of a car can be observed in the compression and extension of its springs. The energy in a compressed spring is given by the equation

$$\mathrm{E} = \int F dx = \frac{1}{2} kx^2 .$$

Using an experimentally determined value for k of 1.2 x 10^5 N/m, we find that for a 3,500-pound automobile, vertical displacements store the amounts of energy in a single spring as shown below. We note that heavy truck springs are much stiffer.

1 cm displacement: 6 J	Summing over four wheels	**24 J**
3 cm displacement: 54 J		**216 J**
6 cm displacement: 216 J		**864 J**
9 cm displacement: 486 J		**1994 J**

We have approximated city driving by assuming that the springs undergo vibrations of magnitude 2 cm at a frequency 3 Hz, keeping in mind that work is done both compressing and extending the spring so that energy can be harvested from both of these motions. Based on these assumptions, a one hour drive generates 1.34 kilowatt-hours of energy available to harvest.

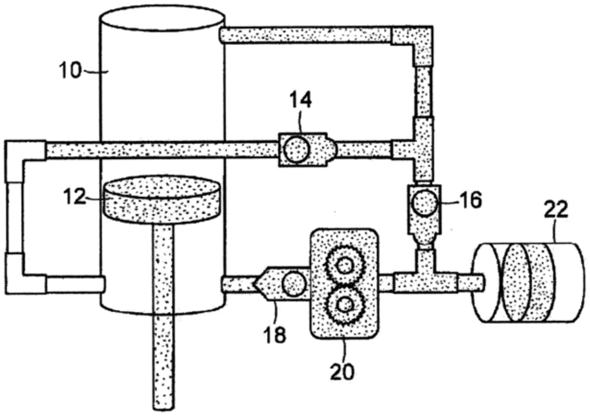


Figure 3: GenShock in its equilibrium state.

With reference now to the drawing, Fig. 3 illustrates the overall system in a first embodiment. Shock body 10 is a cylinder in which a piston 12 resides for reciprocating motion. Check valves 14, 16, and 18 control the flow of hydraulic fluid. The system also includes a hydraulic motor 20 and a capacitive reservoir 22.

Flow of hydraulic fluid upon compression of the piston 12 will now be described in conjunction with Fig. 2. As the piston 12 is compressed, pressurized hydraulic fluid builds in the top part of a chamber 24 and is passed through the check valve 16. Check valve 14 prevents the hydraulic fluid from flowing into a bottom chamber 26. After passing through the check valve 16, the fluid is directed into an hydraulic motor 20 and into a capacitive reservoir 22. The capacitive reservoir 22 acts to store any impulsive pressure surges and smoothes out the pressure of the hydraulic fluid as it is fed into the hydraulic motor 20.

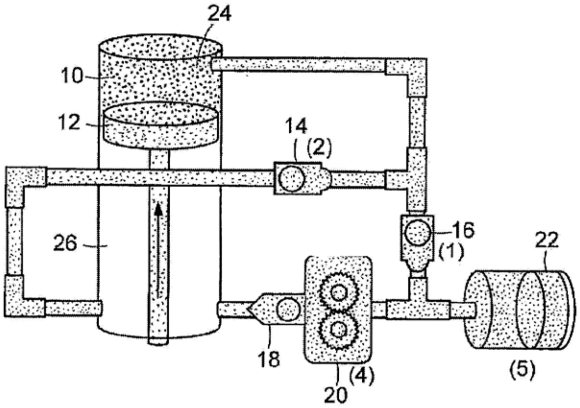


Figure 4: GenShock in its compressed form.

With reference now to Fig. 4, as hydraulic fluid passes through the hydraulic motor 20, it rotates the motor's shaft. The shaft of the motor 20 is coupled to a generator 50 such as a permanent magnet generator. The output of the generator may charge a battery or power an automobile's electric systems when the hydraulic motor turns. Power electronics is connected to the output of the generator 50 as will be described below.

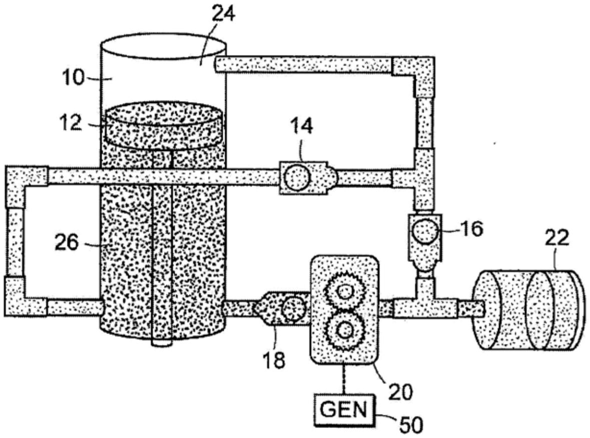


Figure 5: After a finite amount of time of compression, the reservoir below the piston head draws vacuum and sucks the fluid into it.

Fig. 5 illustrates fluid flow as the piston 12 extends. When the piston 12 moves downwardly, pressurized hydraulic fluid is compressed in the bottom portion of the chamber 26 and passes through check valve 14. Check valve 18 prevents the fluid from flowing back into the hydraulic motor 20. The fluid passing through the check valve 14 flows into the top chamber 24.

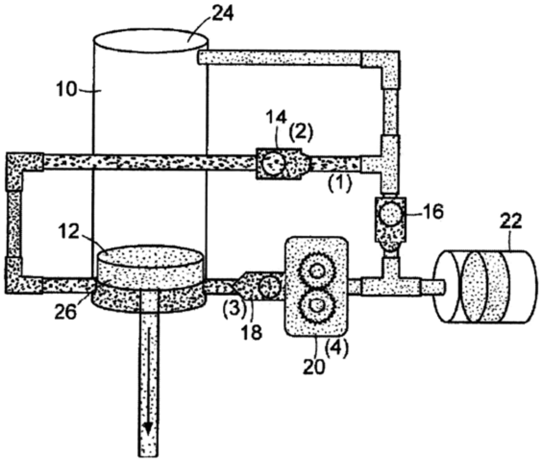


Figure 6: GenShock in its relaxation stage.

Flow characteristics of at least one of the fluid flow circuits may be selected to provide an effective damping in addition to recovery of energy. In this way, the system of the invention not only provides for energy recovery, but also effective damping for wheel control, thereby eliminating the need for a conventional shock absorber.

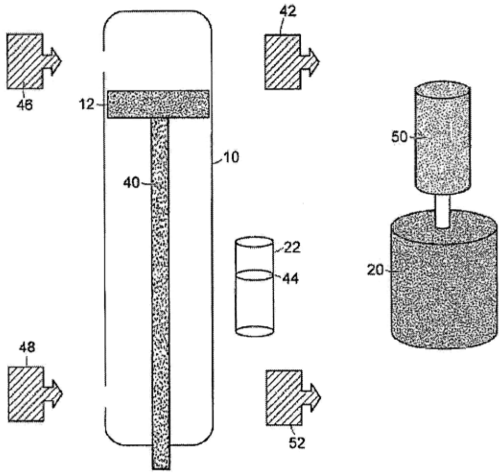


Figure 7: Another embodiment of GenShock. GenShock components.

Yet another embodiment of the invention is shown in Fig. 7. This embodiment allows energy to be recovered during both compression and extension of the piston. As the piston 12, supported by a shaft 40, is compressed hydraulic fluid will pass through a check valve 42 and into capacitive reservoir 22 and includes an emulsion diaphragm 44 that accommodates piston shaft 40 volume that is introduced upon compression stroke of the system. Hydraulic fluid also flows into hydraulic motor 20 and returns to the shock body 10 through check valves 46 and 48. The hydraulic motor 20 actuates an electric generator 50. A suitable electric generator 50 is a permanent magnet generator/DC electric motor.

Upon extension of the piston 12, hydraulic fluid passes through a check valve 52 and into the capacitive reservoir 22 and on through the hydraulic motor 20. As before, hydraulic fluid returns to the shock body 10 through check valves 46 and 48. Note that upon compression and extension of the piston 12, hydraulic fluid flows in the same direction through the motor 20 thereby turning its shaft in the same direction for actuating the electric generator 50.

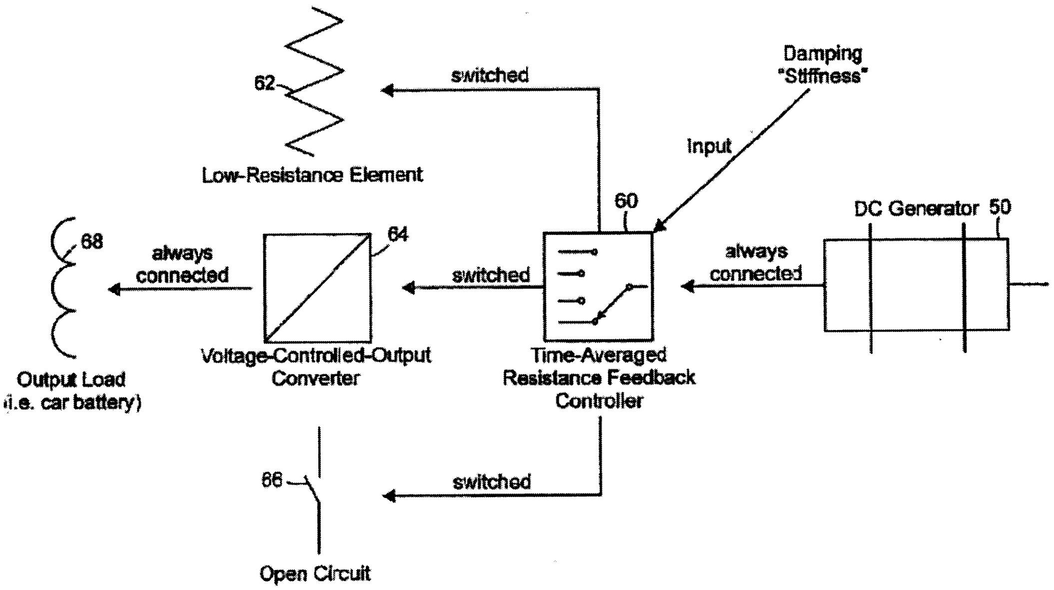


Figure 8: GenShock power electronics schematic. System controls the damping applied to the hydraulic motor for appropriate suspension control.

The power electronics to implement the regenerative shock absorber of the invention will now be discussed in conjunction with Fig. 8. The output of the generator 50 is connected to a time-averaged resistance feedback controller 60 that switches the output from the DC generator 50 among a low resistance element 62, a voltage controlled output converter 64, and an open circuit connection 66. The output of the voltage controlled output converter 64 is always connected to an output load such as a car battery 68. A voltage controlled output converter is not necessarily a buck/boost converter; however, a buck/boost converter is one type of voltage-controlled output converter. We mention the buck/boost converter because it is one common way of implementing a voltage controlled converter. The voltage controlled output converter 64, sometimes referred to as a buck/boost converter, and with a voltage-feedback circuit adjusted to a reference voltage maintain a given output voltage level. This arrangement allows several regenerative shock absorbers to be wired in parallel and setting the voltage reference insures safe voltage output. A diode (not shown) in the converter 64 insures that power can only flow out from the generator 50. A filtering capacitor (not shown) on the input of the converter maintains voltage to the input of the converter even while the time-averaged resistance feedback controller switches the generator between multiple elements. In order to control the rate of damping, the generator 50 output is switched between the resistive element 62, the buck/boost converter 64, and the open circuit connection 66. For a typical output load (such as an uncharged car battery), this mode results in heavy, moderate/heavy, and no damping (ignoring friction), respectively. Using pulse width modulation (PWM) to switch between these alternatives at a high rate allows very selective control over damping. Since output power is only derived while the generator 50 is connected to the buck/boost converter 64, the controller 60 is biased to use this connection over switching between the resistive and open connection. Typically a microcontroller with appropriate sensors to determine the resistance seen by the generator is used for this controller 60. Switching speeds for both the resistance feedback controller 60 and the converter 64 are selected to ensure the converter 64 and its input capacitor are able to continuously conduct.

The controller 60 modifies the resistance across the generator 50 winding, thus affecting the damping characteristics of the shock absorber and adjusting the output voltage enabling the system to be safely connected to several types of loads. As mentioned above, resistance across the generator winding is achieved by switching the output leads of the generator 50 between the three sources: the low resistance element 62, the converter 64, and the open circuit 66. The low resistance element 62 (such as a closed-circuit connection (a wire)) creates high damping force. The open circuit connection 66 provides very low damping. Depending on the load connected to the output of the converter 64, the converter provides differing damping force. The controller 60 preferably uses feedback to achieve a given time averaged effective resistance across the generator 50. This feedback may come from sensors such as a voltage and current sensor placed across the generator terminals. This resistance can be set by the manufacturer, the driver (to dynamically adjust the suspension dynamics based on road conditions, driving, or cargo), or even by sensors such as strain gauges that adjust damping based on cargo weight. Adjustment of output voltage is achieved solely by the converter 64. The converter 64 has its own feedback loop that maintains a constant voltage output, when powered. Since input power from the suspension is varying, the converter 64 holds the voltage steady while allowing current flow to fluctuate. The converter 64 circuitry is similar to a standard buck/boost converter with negative feedback based on output voltage. This arrangement insures power only flows out (the load is unable to drive the input, in this case, the generator). Capacitors (not shown) smooth the output voltage. It is noted that any type of efficient converter that is able to maintain a given voltage, ensure one-way current flow, and have sufficient input filtering to accommodate a PWM input, can be used. The buck/boost converter 64 is merely one such example.

Depending on switching duty cycle, this circuitry has the effect of either reducing the output voltage or increasing output voltage. Duty cycle is controlled via a feedback loop that maintains a given output voltage. Neglecting parasitics, the buck/boost converter 64 operation is perfectly efficient. Thus for the regenerative shock absorber disclosed herein connected to a conventional 12v car battery, the converter 64 will convert 6v at 1A from the generator into 12v at 0.5A. Likewise it will convert 48v at 1A into 12v at 4A. Note that the voltage stays constant regardless of the input, but the current changes. Power is conserved and all the energy from the generator is harvested for use.

The arrangement in Fig. 8 is able to dissipate energy as heat through the resistive element 62. If, for example, the regenerative shock absorber of the invention is connected to a fully charged battery, no more energy can safely go into the battery. Thus it is as if the system is disconnected from a load. With a naive implementation, this would result in the generator having near infinite resistance between its terminals, resulting in zero back-EMF. Without back-EMF there is no damping in the suspension (other than from frictional sources), and the shock absorber does not serve its primary purpose of damping suspension movement. This error case is solved by selectively dissipating energy as heat through the resistive element 62. The circuitry can pulse-width-modulate a connection between the generator windings and a low resistance element. This low resistance connection will allow the generator to produce back-EMF proportional to the shaft velocity and inversely proportional to the connection resistance. No energy is harvested for use in this mode. When the generator 50 is connected to the open circuit connection 66, the generator winding is disconnected from the load. The generator output is effectively an open-circuit. Very little back-EMF is produced and no energy is harvested for use in this mode.

The power electronics discussed above in conjunction with Fig. 8 achieves four objectives. First, the circuitry provides generator isolation to insure that each shock operates independently of the output load it is connected to, i.e., battery voltage. Second, the system provides variable damping that is electronically modified either by the user or automatically via sensors such as a strain gauge sensor that adjusts performance based on vehicle weight. These sensors merely change the reference resistance that the resistance feedback controller adjusts for. The system also enables operation with multiple units by matching voltage between multiple units wired in parallel. Finally, the circuitry provides battery-safe charging by regulating output voltage to safe levels.

The regenerative shock absorber of the present invention is applicable to any wheeled vehicle; heavy trucks remain a compelling target because of their substantial weight and high suspension spring stiffness. This technology is also suitable for military vehicles.

WORKING FLUID

The conversion of linear to rotary motion is the basic mechanism that enables GenShock to harvest the wasted energy of a vehicle's suspension system. It is accomplished via hydraulics and the working fluid remains an essential component to investigate for optimal recovery. The viscosity of this fluid is of particular interest as it directly correlates to how pressure in the fluid flow is transduced to rotational motion of the hydraulic motor.

For reference, water is considered a low kinematic viscosity fluid at 1 centistoke (cSt) with units cm^2/s. Honey at room temperature approaches roughly 10,000 cSt. The

Newtonian fluid used in GenShock must lie at an optimal midrange between these extremes. Too low a viscosity, there are losses in the pressure drop across the hydraulic motor. At the same time, however, there is less shear force experienced in bends around the fluid circuit. With a high viscosity fluid, there is highly effective power transfer at the hydraulic motor end, but losses sustained in the fluid circuit due to shear forces against the tubing walls. Intuitively, the comparison of a semisolid-liquid versus a non-viscous liquid transferring momentum to a waterwheel, the power transduction is most effective in the semisolid case. It is the purpose of this investigation to experimentally verify by way of empirical data, where the midpoint lies for power transduction optimization in the working fluid of this hydraulic regenerative shock absorber.

Physical properties of each fluid was sought after, however industrial fluid suppliers do not provide this information readily.

METHOD

A custom GenShock prototype was fabricated for the purpose of this investigation per the description in the background section. The filling mechanism was designed to investigate five different viscosity working fluids: 100cSt, 122cSt, 132cSt, 160cSt, 200cSt. These were chosen based on mainly ease of availability as much fluid was needed to be purchased over the course of this research.

In the fabrication process of the GenShock prototype, much care was taken to ensure a fluid-tight system. TIG welding was performed at the fluid outlets from the main shock body. NPT fittings were used in all peripheral hosing and hydraulic connections. Machining of the custom top-cap for retrofitting on an military HMMWV was performed on a CNC mill and lathe. Tolerances were of utmost concern and a final soap-water and air pressure test was performed so that all leaks were detected.

The filling of fluid within the GenShock prototype is a difficult task considering that all air bubbles must be evacuated from the system. Should there remain air bubbles trapped within the fluid, it poses the issue of both cavitation and air-pocket compressibility. Upon sharp compressions and relaxations of the shock, the gaseous pocket will compress and expand which leave the fluid unmoving. This is an issue that has a catastrophic effect on the efficiency of GenShock. The evacuation of the bubbles was accomplished via a vacuum pump attached to the output hose of the piston. Bubbles were essentially pulled out of the system by buoyant forces within the working fluid.

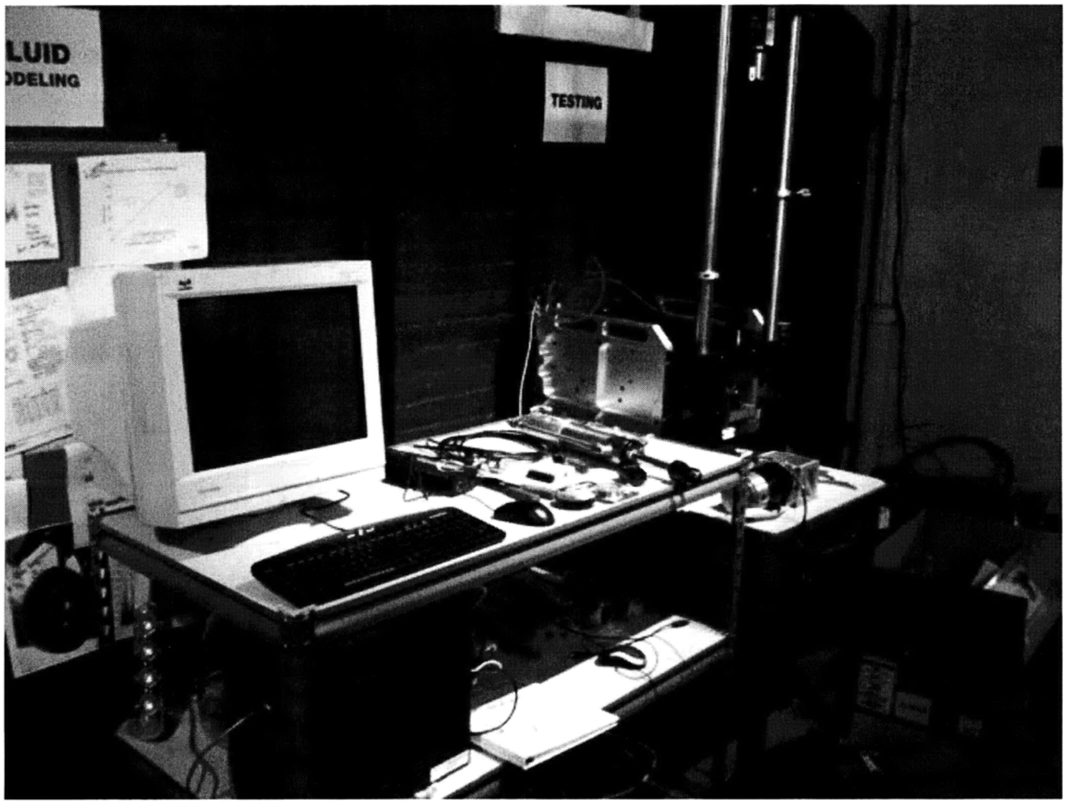


Figure 9: Hydraulic Dynomometer apparatus setup for GenShock testing purposes in this investigation.

Actual testing of working fluid performance was done on a Roehrig Dynomometer. This instrument is similar to an Instron machine used commonly in the MIT Department of Materials Engineering, however the dynomometer (dyno) is built specifically for the testing of shock absorbers in that it is capable of vertical velocities ranging from 0 in/s to 50 in/s. These are the extreme velocities seen by a vehicle's suspension in all cases: off-roading to the smoothest of highways.

There are many types of dynos available, but the one used for GenShock testing was of a crank design. It is essentially a camshaft attached to a variable DC electric motor on the order of 5 horsepower. It is capable of loads up to 3,000 lbs at the speeds ranging from 0 in/s to 50 in/s. As the cam rotates, its center point traces a circle of a fixed radii depending on input. Consequently, this instrument is only capable of sinusoidal motion to apply to the shock. Nonetheless it effectively serves the purpose of this investigation.

RESULTS

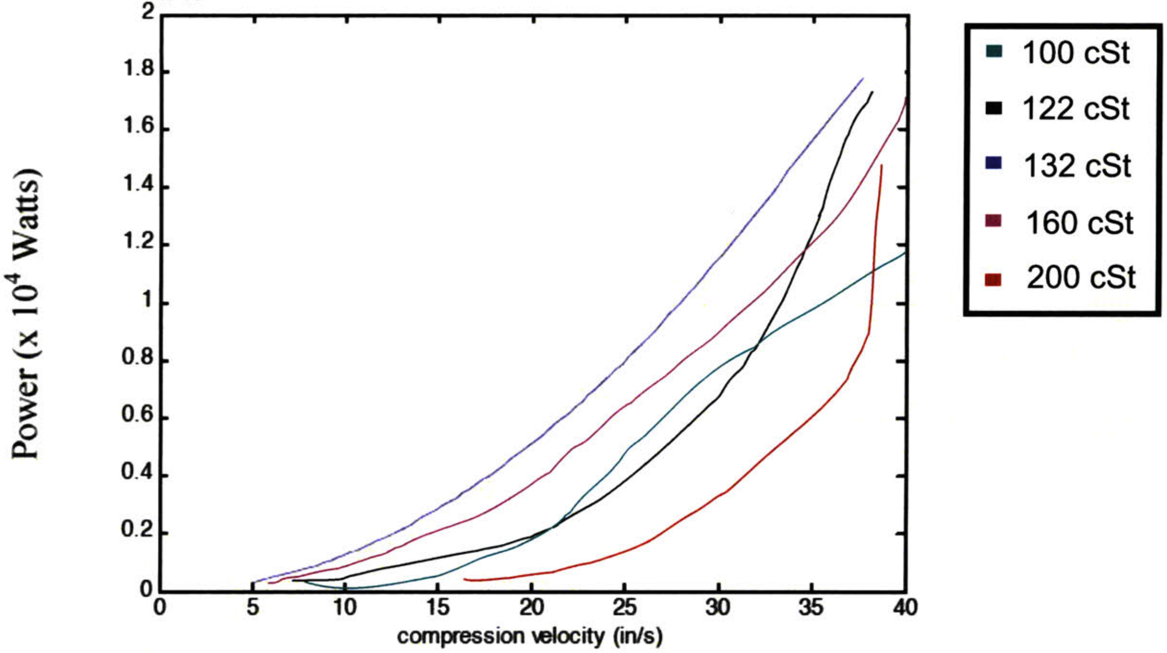
Per the method described, five different working fluid viscosities were tested in the GenShock system: 100 cSt, 122cSt, 132cSt, 160cSt, and 200cSt. The testing was performed on a 5 hp dynomometer where the entire GenShock hydraulic system was mounted to undergo sinusoidal oscillations, one degree of motion.

The hydraulic dyno is capable of a maximum energy input of 4,000 watts of power. The resulting energy output from the GenShock system was recorded for efficiency measurement purposes.

Plot 1 illustrates the GenShock power output with the different fluids. Voltage was measured via the power electronics system and catalogued as a function of the vertical velocity of the shock dynomometer. Instantaneous readings were taken from the dynamometer at steps of the sinusoid, and the corresponding power outputs from the electrical generator were noted. Here it is noted that the range of power outputs at a fixed compression velocity of the shock absorber indicate that the working fluid viscosity of GenShock presents a very important parameter for choosing. For example, at 30 in/s shock velocity, the power output ranges between approximately 400 watts and 1,200 watts. Plot 1 essentially demonstrates that selection of fluid is indeed a large factor in the effective transduction of power from fluid pressure flow to rotational motion of a hydraulic motor. The difference between 132 cSt and 200 cSt at 30 in/s represents a 66% increase in effective transfer of momentum. This is substantial and indicates that careful selection of fluid is important.

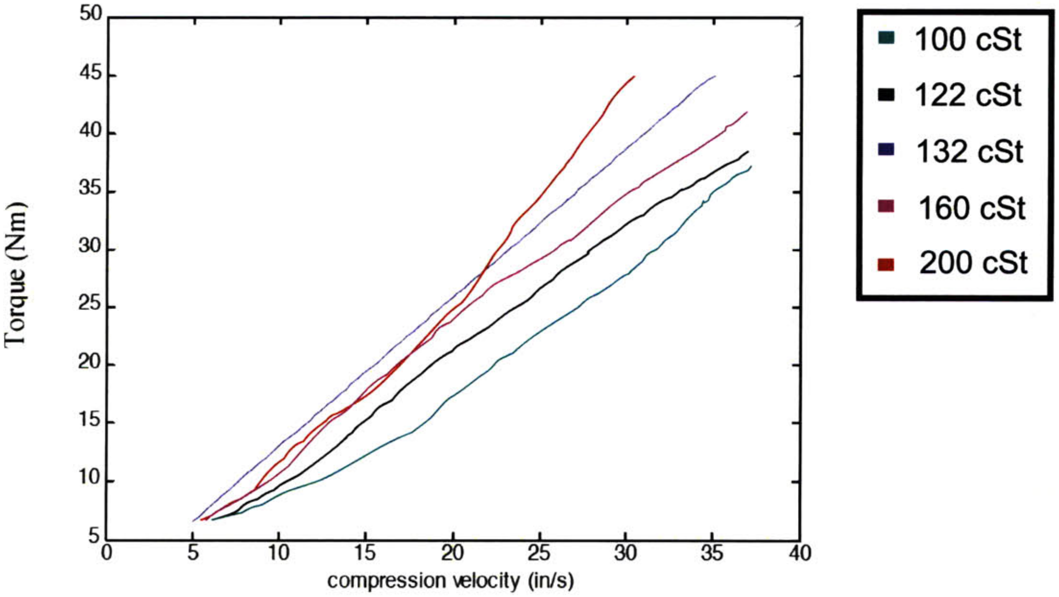
The fluids between 100 cSt and 132 cSt, and 132 cSt and 200 cSt, do not demonstrate optimized momentum transfer properties. Despite the fact that Plot 2 indicates that the 200 cSt fluid was most effective in the torque output of the hydraulic motor, it performed the worst in the power generation, the plot that truly demonstrates which fluid is best for GenShock application. The 200 cSt fluid was not suitable for this application given the bends the fluid is required to pass through. The shear forces that are passed on between the fluid and walls of the fluid circuit present a great energy sink in the process of recapturing as much kinetic travel as possible in the vertical movement of a vehicle.

Generator Electrical Power Output



Plot 1: GenShock power output via the electric motor/generator. Permanent magnet. As seen, the 132 cSt fluid is most optimized for GenShock power output in comparison to other fluid choices. 200 cSt is worst.

Hydraulic Motor Torque Output



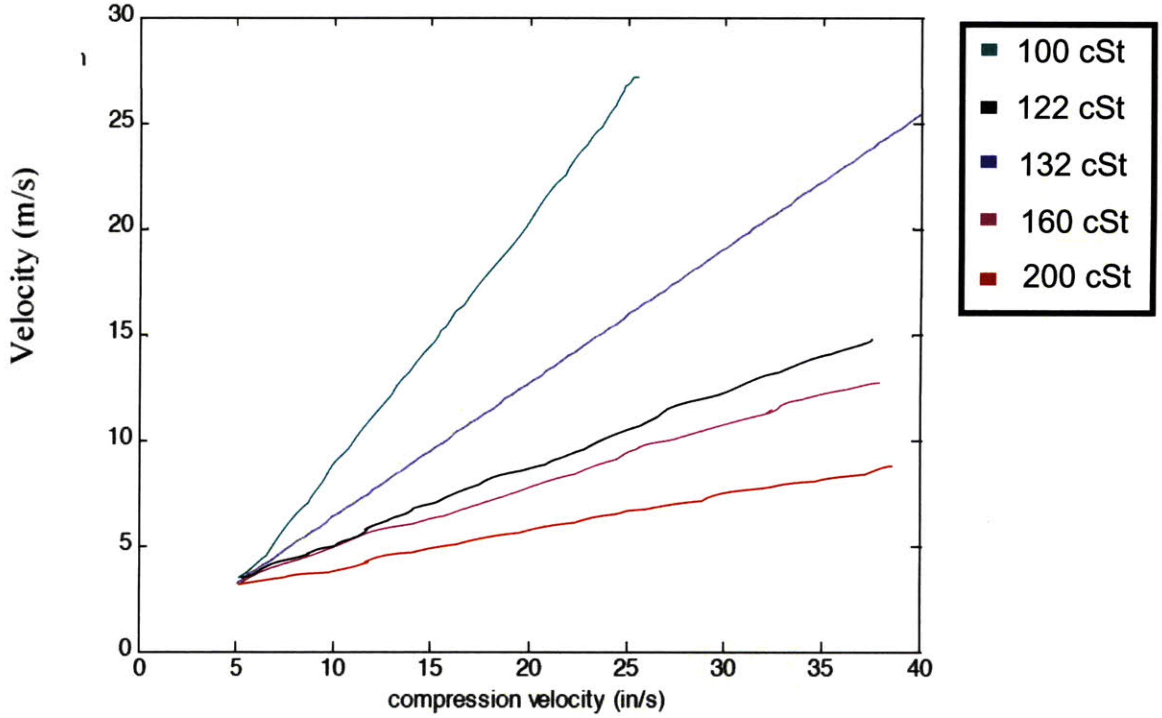
Plot 2: Hydraulic motor torque output from GenShock. Higher viscosity fluids are more conducive for efficient momentum transfer to the hydraulic motor.

Plot 2 is an indication of the torque output of the hydraulic motor as a function of shock compression velocity. A strain gauge was placed at the end of the hydraulic motor in each of these tests and resultant torques were measured empirically. The digital 30332B Honeywell torque gauge interfaced with the shock dynomometer Roehrig software and tabulated torques as a function of the linear compression velocity of the shocks. Here it is clear that the most effective torque transfer to the hydraulic motor rests in the higher kinematic viscosities of the fluid. As shown, the 200 cSt fluid was capable of almost 45Nm at 30 in/s vertical shock velocity. In contrast, the lowest viscosity fluid, 100 cSt, was capable of only 26 Nm at the same vertical shock velocity.

Close to consistent with initial suspicion, the hydraulic motor torque output decreases almost linearly with decreasing viscosity. Therein lies the viscosity balance problem; to maximize the effect of increased viscosity for effective momentum transfer to the water-wheel type hydraulic motor but, at the same time, minimize the losses incurred in the tubing of the hydraulic circuitry. Viscous fluids tend to impart large shear forces to the side walls of their container.

During testing, it was easily detectable how the fluid changes affected system response in the dynomometer. The prototype designed for this investigation included flexible hosing which, given compression and relaxation of the more viscous fluids, underwent a significant degree of flexing. This means that the actual volume within the tubing of GenShock was changing simultaneously presenting potential issues that may have affected torque and power output data.

Fluid Velocity in 3/8" Tubing

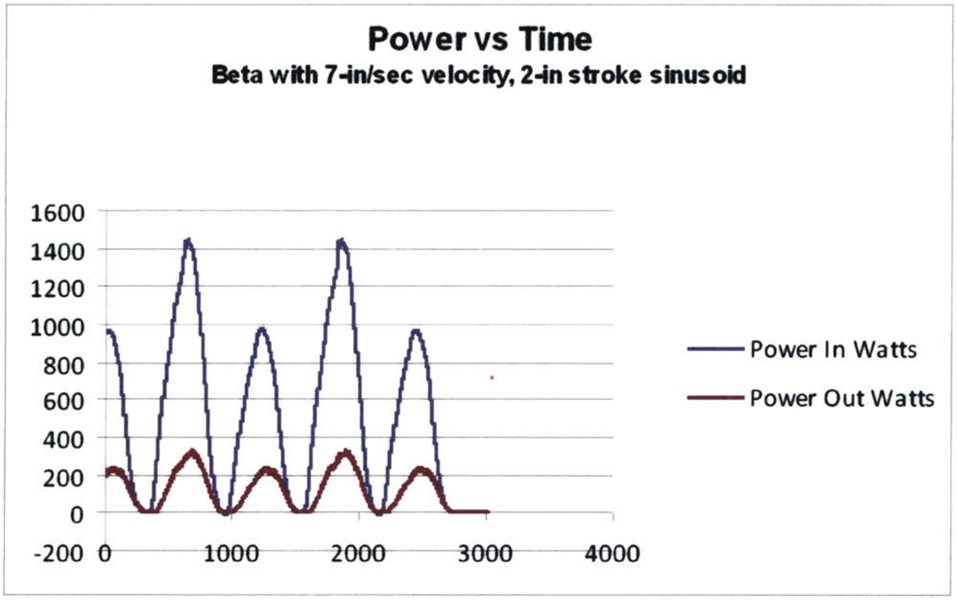


Plot 3: Fluid velocities measured experimentally in the GenShock system. Higher viscosities impart high shear forces against the tube walls, thereby creating friction and generating heat. This slows the movement of the fluid and decreases efficiency of the system.

The fluid velocity, as illustrated in Plot 3, within the tubing of GenShock was calculated via meter flow sensor installed at a fluid outlet from the main shock body. This sensor indicates volumetric fluid flow with respect to time. Per the data, it is clear how the viscous fluid introduce tremendous losses in the system. It is a linear correlation in the plot, as the highest fluid velocities are attained with the lowest viscous fluid, and the slope begins to decline incrementally with more viscous fluids.

Similar to what was discussed previously, the higher viscous fluids impart large shear forces against the walls of its container. This is a large problem simply because the

GenShock system incurs a high degree of its losses due to fluid heat generation. Any generation of heat means losses for GenShock, something that is avoided under economic conditions. High fluid velocities in the tubing are facilitated by lower kinematic viscosity fluids, but again have the issue of imparting less momentum to the hydraulic motor when a pressure differential is applied across it.



Plot 4: Efficiency plot of Dynomometer energy input to GenShock electricity output with 132 cSt fluid. This plot indicates a 25% efficiency performance of the GenShock system.

DISCUSSION & CONCLUSION

The purpose of this investigation was to identify the significance of fluid viscosity in a hydraulic-based regenerative rotary shock absorber. The investigation yielded results that indicate that viscosity is indeed an important factor to consider for maximizing the transduction of power from fluid flow to the rotational motion of a hydraulic motor. A balancing act between viscous fluid for maximal power transfer and viscous losses within the fluid circuit must be entertained carefully. This study demonstrates that the 132cSt fluid was the ideal choice for the system.

Referring to Plot 2, an increase of torque by 46% from a 100cSt fluid to a 200cSt fluid is highly substantial and confirms the initial theory that a fluid which approximates a semi-solid can more effectively transfer momentum than a fluid much less viscous. On the other hand, Newtonian fluids are incompressible. The question that remains post the experimental validation of viscosity importance in power transfer is in explaining the degree of significance (i.e. 46%) between two fluids that have viscosities set apart by 100cSt.

Water (1 cSt at room temperature) compresses approximately 1% for every 10atm of pressure applied. From this standpoint, it does not entirely make sense how fluids on the order of 100 and 200cSt can present such a great deal of change to power transfer because both are incompressible fluids and do not differ in their compressibility by much. It may be prudent to investigate this matter further in a more theoretical based standpoint than the engineering standpoint with which this study was conducted.

Some variability in the GenShock fluid velocity, hydraulic torque output, and electrical motor output can be ascribed to the problem of air bubbles. The filling mechanism of the various fluids is subject to a great deal of variability. Vacuum was drawn within the system by a hydraulic pump and fluid was drawn in. However air bubbles mixed in the fluid were also drawn into the system. In order to remove the air bubbles, the GenShock system was placed under high internal pressure to force the bubbles out of the fluid. This worked somewhat effectively, however there did remain a few air bubbles in the system lending to irregular behavior in damping characteristics of the shock absorber.

Fluid losses must be taken into serious consideration in any hydraulic system, and in GenShock it is a balancing act between power transduction and minimizing fluid shear forces against the tube walls. An initial idea within the scope of this investigation was to use Magnetorheological fluids (micron-sized iron filings in suspension) that can effectively change their viscosity with an applied magnetic field. The idea could enable the liquid to be highly viscous in the part of the circuit that mattered: the hydraulic motor. Whereas the fluid could be relatively non-viscous in the remaining part of the circuit to minimize shear forces against tube walls.

Currently, magnetorheological fluids produced by Lord Corporation are being used for variable damping shock absorbers. Coil windings are placed around the choke valve of the shock body. When energized, the coils create a localized B-field which re-orient the iron filings in the fluid per the magnetic flux lines. By so doing, the fluid instantaneously changes its viscosity. Drawing inspiration from this phenomenon of localized viscosity change, it occurred to me that it could potentially be effective for use in more effective power transduction to a hydraulic motor.

A major obstacle faced in this phase of the study was simply that the Magnetorheological fluids damaged the internal components of GenShock due to the micron-sized filings in the suspension. Hydraulic motors are not designed to be struck at high forces with metal particles. The kinds of pressures that GenShock sees from vertical shock velocities that often times spikes up to 30 in/s can reach up to 1,000 psi. At these pressures, miniature particles within the fluid pose great harm to the system: the hydraulic hosing, the welds, and even fixed corner connections. It remains a fascinating idea that could potentially assist in the findings of this study, enabling hydraulic fluids to maximize their viscosity at a transduction node and minimize their viscosity elsewhere.

REFERENCES

1. Dixon, John C. Shock Absorber Handbook, West Sussex, England. Wiley, 2007.
2. Evett, Jack. Solved Problems in Fluid Mechanics and Hydraulics. Charlotte, NC. McGraw-Hill, 1989.
3. Merritt, Herbert. Hydraulic Control Systems. NY, NY. Wiley, 2001.
4. Hallow, James. Car Suspension and Handling. San Francisco, CA. Scholastic, 2000.
5. Lu, Kunquan. Electrorheological Fluids and Magnetorheological Suspensions. Proceedings of the Ninth International Fluids Conference. Beijing, China. 2003.
6. Nunney, M.J. Light and Heavy Vehicle Technology. Burlington, MA. Elsevier Publishing, 2003.
7. Yeaple, Jon. Fluid Power Design Handbook. NY, NY. Wiley, 1995.