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Application of the Principle of Compressible flow in the Conservation of Energy and performance characteristics of Hydraulic Dampers

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Abstract

Research has revealed that there is a lack of effective conservation of energy models that relates to the energy in hydraulic dampers during damper operation. This is more visible after the Computational Fluid Dynamics simulations study revealed that the fluid in a hydraulic damper, during damper operation, experiences transformations. These transformations are caused by variations experienced by the hydraulic fluid dynamics due to pressure changes that results from piston displacement, which generates energy during damping and the generated energy can be used to power other vehicle mechanical components. Previous studies on energy harvesting during damping are facing major challenges. These has limitations on the current developed models which focused on performance characteristics of dampers without exploring all major energy parameters during damping.

In the current study, the application of Computational Fluid Dynamics, Fluid Compressible flow and stochastic models are used to model the random phenomenon during the damping process. The proposed models revealed that there is a clear correlation between fluid compressibility and relevant fluid parameters such as fluid pressure (p), fluid density (ρ), fluid velocity (V) and the total energy conserved (E). These models also revealed that acceptable energy can be harvested which can be used to power other vehicle mechanical components.

Keywords: Energy dissipation, Modelling, Conservation of Energy, Compressible flow.

INTRODUCTION

A hydraulic damper is a device which assist in protecting the components of a vehicle's isolated side, the chassis, from the movement and acceleration of the vehicle's input side i.e. the wheels. Whilst the hydraulic damper ensures a better ride quality, it absorbs and damps the shock impulses by converting kinetic energy, caused by the spring of the suspension system, into thermal energy [1]. This energy is dissipated in a form of heat which results as a loss of energy that could be otherwise conserved to power alternative mechanical systems in an automobile. In acknowledgement that the operation of a hydraulic damper system results in thermal energy loss, it was revealed that, on average, the energy generated in a hydraulic damper system can go up to 40-50W [2]. Studies further showed that based on road roughness and vehicle dynamics an estimation of 100 – 400W of power was lost in the Damper system of a typical middle sized passenger car when travelling at 100km/hr. on good to average roads [3].

Since Energy is the most important of all resources, its sustainability has become an important aspect nationally if not globally and the demand for Energy in a safe and environmentally friendly manner is a key challenge. From the year 2014 to date, the global demand for Energy has increased and it is predicted that by the year 2040 the demand would have increased by 25%. In response to this prediction it became of importance to realise that renewable sources alone will not keep up with the growing demand because the demand for and use of Energy varies considerable with time.

Through the understanding of this challenge, one of the most important issues is how can knowledge of engineering dynamics contribute to generating a solution for maintaining sustainability. Understanding of this current challenge makes the practicability of harvesting and converting Energy a necessity thus contributing to the sustainability of our most valuable resource. With response to this statement, work was done to find methods that can allow the dissipated energy of hydraulic dampers to be conserved.

New technologies, like Regenerative systems, which can capture and re-use vehicle Energy from various possible sources gained importance [1]. Kinetic Energy Recovery systems, *KERS,* are used to capture a Vehicle's kinetic Energy, which is wasted as heat in braking, and re-used to power the vehicle.The design of *KERS* directed ideas for similar concepts of which these can be used in the automobile Damper system, where Energy dissipated through Damper systems can be harvested and re-utilized to power auxiliary systems. The practicability of a system that can capture and harvest Energy from the Damper system was investigated, since from study and analysis it was found that heat generated in a Damper system results from the dissipation of kinetic Energy caused by the forces i.e. fluid pressure force, fluid viscous force and fluid inertial force, generated inside the suspension cylinder during the compression and rebound strokes of the system. During the compression and rebound process the displacement of the piston inside the cylinder allows the hydraulic fluid inside the cylinder to experience change in pressure, the magnitude of the pressure is so high that heat is generated and dissipated. A need to design a system that would be easily integrated into cars, and the possibility to locally use the recovered Energy to add new functionalities that can improve the security or the comfort of a car, and the necessity to not degrade and, if possible, to improve the performance of suspensions is of importance towards contributing to the sustainability of Energy was worth analysis [4, 5-7]. Even though there was work done on regenerative systems it was discovered that the automobile industry experiences a *lack of effective Conservation of Energy Models* that can give information about the amount of energy inside a damper system whilst in operation

In support of working towards the sustainability of energy in the automobile industry, this paper was aimed at *Modelling the Conservation of Energy in a twin tube hydraulic damper system* during damper operation by application of the concept of compressible flow and dimensional analysis. The success of the model was able to quantify the amount of energy during damper operation which can serve as an aid in selecting suitable Twin Tube hydraulic damper system.

Regenerative Technology systems that can be used in damper systems. As with each operation; depending on the degree to which the fluid parameters experience change; knowledge about the total energy in the damper can allow a suitable regenerative system to be adopted.

METHODOLOGY

Theoretical consideration for Modelling the Conservation of Energy in a Twin Tube hydraulic damper.

Modelling is the activity done to describe a system or process which can be used to explain it. In deriving the theoretical model for the Conservation of Energy in a Twin Tube Hydraulic Damper system, the consideration of model equations with similar energy parameters were important. The understanding of the various forces acting on the hydraulic fluid during damper operation and the parameters which influenced these forces were also important factors which guided the selection of the suitable model. The application of Compressible Flow and Dimensional Analysis were also of great importance in Modelling the Conservation of Energy of a

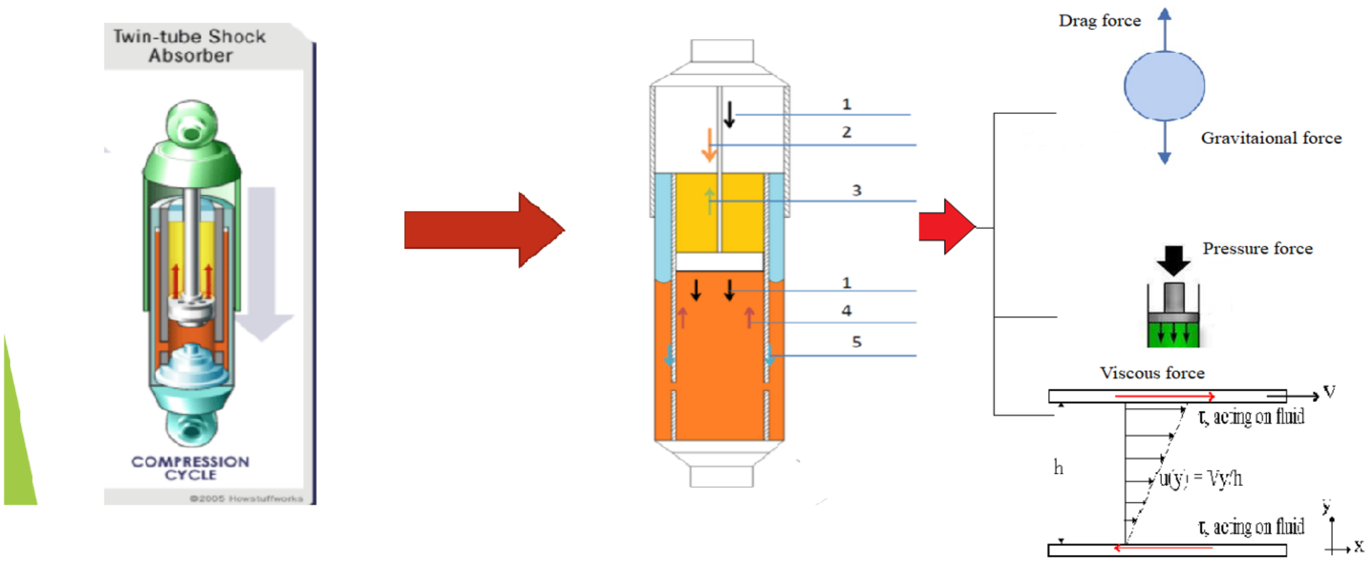

Figure 1.1: Setup of Twin Tube damper system.

1. Pressure force, 2.Gravitational force, 3.Drag force, 4.Inertia force, 5.Viscous force.

With reference to figure 1.1 and understanding the relation between Fluid mechanics and Thermodynamics, it became of note that work and heat are inter-related concepts. Work is a force used to transfer energy between a system and its surroundings, and this work is used to create heat resulting in the transfer of thermal energy. Both work and heat together allows transfer of thermal energy.Internal energy refers to the energy within the hydraulic system which includes kinetic energy of molecules and the energy stored in the chemical bonds between molecules. With the interaction of work, heat and internal energy, there is energy transfer and conversions every time a change is experienced by a system.This model was expressed as follows:

$$e = U + \frac{1}{2}V^2 + gz \tag{1}$$

Where e= Total energy of the fluid per unit mass (J/kg), U=Internal energy per unit mass (J/kg), $\frac{1}{2}V^2$= Kinetic energy per unit mass (J/kg), Gz= Potential energy per unit mass (J/kg).

For consideration of the pressure difference in the pressure chambers as fluid flows through flow paths, it was advisable by energy principles to account for non- uniform inlets and exits of the fluid through valve orifices. For this reason a correction factor for the velocity and kinetic energy term was introduced. This factor was modelled as:

$$\alpha = \frac{1}{A}\int (\frac{U}{Vave})^3 \, dA \tag{2}$$

Where, A= Area of geometry (m^2), U= Internal Energy (J), Vave = Average velocity(m/s). $V_{ave} = \frac{1}{A}\int UdA$.

With knowledge from the principle of Conservation of Mechanical Energy, an isolated system that is only subject to conservative forces, the mechanical energy is constant. The Mechanical Energy was mathematically expressed as:

$$E_M = E_K + E_P = \frac{1}{2}mV^2 + mgh \tag{3}$$

Where, E_K = Kinetic Energy of system (J), E_P = Potential Energy of system (J), m = Mass of object (kg), V= Velocity of object (m/s), g= Acceleration due to gravity (m/s^2), h= Height, position of object (m).

The Bernoulli Model is applicable to the Conservation of Energy principle appropriate for flowing fluids. This model was collectively developed by'*Daniel Bernoulli'*. The model is mathematically expressed as:

$$\frac{P_1}{\rho g} + \frac{{V_1}^2}{2g} + Z_1 = \frac{P_2}{\rho g} + \frac{{V_2}^2}{2g} + Z_2 \tag{4}$$

Where, P = Fluid pressure (Pa), ρ = Fluid density (kg/m^3), g = Acceleration due to gravity (m/s^2), Z = Height, position of object (m), V = Velocity of fluid (m/s).

Application of Compressible flow and Dimensional Analysis with in deriving the suitable model.

By studying the operation of the damper system, it was noted that the internal parameters which experiences change during operation are fluid density and fluid velocity due to change in fluid pressure. With this understanding it was logical to express the forces which acts on the fluid in terms of the parameters which change with the area of contact. This approach was beneficial as it helped understand the relationship that these forces have on the parameters of study since each model is associated with certain parameters which can be measured. For analysis, if a force (F) were to be applied on a pressure (P) and cross sectional area (A) of an object of mass (m) in a manner that it moves with an acceleration (a)- This same force can be measured in two different ways which is either: by measuring the mass and acceleration of the object and using the Second Law of Newton to obtain the force from F=ma, or similarly the force can be obtained by calculating the product of the pressure magnitude and cross sectional area F=PA. Both relationships gives a force measured in Newton (N).

By using the different ways to measure force as reference, the application of Dimensional Analysis became of importance as this concept helped in expressing the relationship of the forces which acts on the fluid with the parameters which change during damper operation. **Dimensional Analysis:* Is a mathematical technique used in research work for design and for conducting model tests. It deals with the dimensions of the physical quantities involved in the phenomenon. These physical quantities are measured by comparison, which is made with respect to an arbitrary value. Since the mass (m) of the fluid during damper operation can be expressed as

$$m=\rho * V \tag{5}$$

Where: m= mass of fluid (kg), ρ = density of fluid (kg/m^3), V= Volume fluid occupies (m^3). Which the volume can further be expressed as V=AL, where A is the cross sectional area and L the length travelled by the piston. The forces which acts on the fluid was expressed in terms of the fluid parameters which change, the cross sectional area of contact and the length travelled by the piston. These forces were expressed as:

The Pressure Force:

$$F_P = P * A \tag{6}$$

Where P = Fluid Pressure (P), A = Cross sectional area of piston (m^2).

The Gravitational Force:

$$F_g = m * g = \rho * V * g = \rho(AL)g \tag{7}$$

Where: ρ = Fluid density (kg/m^3), A = Cross sectional area of piston (m^2),L = Length travelled by piston (m), g = Acceleration due to gravity (m/s^2).

The Drag Force:

$$F_D = C_D * \rho * A * \frac{V^2}{2} \tag{8}$$

Where:C_D = Constant of proportionality, ρ = Fluid density (kg/m^3), A = Cross sectional area of piston (m^2),V = Velocity of fluid (m/s).

The Inertia Force:

$$F_i = m * a = \rho * A * V^2 \tag{9}$$

Where:ρ = Fluid density (kg/m^3),A= Cross sectional area of piston (m^2),V = Velocity of fluid (m/s).

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The Viscous Force:

$$F_v = \tau * A$$
$$= \mu * V * L \tag{10}$$

Where: μ = Fluid dynamic viscosity (Pa.s), L = Length travelled by piston (m), V= Velocity of fluid (m/s).

The application of Dimensional Analysis was useful because by measuring how the parameters changed allowed the analysis of the forces influencing the fluid during damper operation.

Selection of suitable models.

After the relevant models were selected, it became important to consider the factors which influences the damper process. These factors were crucial as they served as guidance in modifying the above mentioned models, which allowed the objective of '*Modelling the Conservation of Energy in Damper systems*' to be achieved.

The internal factors influencing the work done during the damping process during compression are:

- Oil density ($\boldsymbol{\rho}$).
- Oil pressure *(*$\boldsymbol{P}$).
- Piston diameter and piston stroke length*(.*$\boldsymbol{L}$)
- Velocity of piston ($\boldsymbol{V}$).

By taking these factors into consideration and applying the concept of dimensional analysis, the Mechanical energy model was modified to suit these factors which were also the parameters influencing the energy of the Twin Tube damper system during operation. Henceforth the Mechanical Energy model was expressed as:

$$E_M = E_K + E_P$$
$$= \frac{1}{2}mV^2 + mgh$$

But with the mass of fluid being noted as,$m = \rho * V$and since the kinetic energy is dependent on the change in velocity (V), and the potential energy on the change in length i.e. height, Z, the Mechanical Energy model was modifiedand resulted in:

$$E_M = E_K + E_P$$
$$= \frac{1}{2}mV^2 + mgh$$
$$= \frac{\mathbf{1}}{\mathbf{2}}[\boldsymbol{\rho}\Delta\boldsymbol{V}] * \boldsymbol{V}^{\mathbf{2}} + \boldsymbol{\rho A g}[\Delta\boldsymbol{Z}]^{\mathbf{2}} \tag{11}$$

Where: ρ = Density of fluid, ΔV = Change in volume during operation,V = Velocity of fluid.A = Cross sectional area of piston,g = Acceleration due to gravity,ΔZ = Change in position of piston.

The Kinetic Energy was analysed to be vastly dependent on the density (ρ_2) and velocity (V_2) at the entrance of the reserve cylinder, and the Potential Energy was analysed to depend on the density (ρ_1) in the pressure tube and the change in height (Z) hereof.

By applying the concept of compressible flow for an Isothermal process, between any two given points, the Bernoulli model was modified and resulted in:

$$\frac{\boldsymbol{P_1}}{\boldsymbol{\rho_1}}\boldsymbol{log_e P_1} + \frac{\boldsymbol{V_1}^{\mathbf{2}}}{\mathbf{2}\boldsymbol{g}} + \boldsymbol{Z_1}$$
$$= \frac{\boldsymbol{P_2}}{\boldsymbol{\rho_2}}\boldsymbol{log_e} \quad \boldsymbol{P_2} + \frac{\boldsymbol{V_2}^{\mathbf{2}}}{\mathbf{2}\boldsymbol{g}} + \boldsymbol{Z_2} \tag{12}$$

Where: P_1 = Initial pressure applied/experienced by fluid,ρ_1 = Initial density of fluid,V_1 = Initial velocity during operation,Z_1 = Initial piston position during operation, g= Acceleration due to gravity.

P_2, ρ_2, V_2, Z_2Is the pressure, density, velocity and position during operation at any given point/ instant.

The change in volume,ΔV and change in position of the piston, ΔZ was considered since during the damper operation the hydraulic fluid experiences a change in volume during compression and rebound of the system, while the piston travels a certain distance which depends on the force exerted during the oscillations. The understanding of this concepts was analysed by applying and considering the change in thermodynamic states of the fluid during operation. These concepts thus completed the modification of the selected models which suited the system at hand- The hydraulic damper system.

The relevant models, Bernoulli model and the Mechanical Energy model, as selected was analysed for its relevance in context- As the idea was to *Model the Conservation of Energy in a twin tube damper system*. The application of Computational Fluid Dynamics was considered for validation of the proposed models.

RESULTS AND DISCUSSION

The proposed models in this paper was tested with the properties of the hydraulic fluid, at 15°C, during operation and that of the vehicle. These are: Vehicle mass *m*= 1590kg, velocity of vehicle *V*= 40-60m/s, density of fluid at entrance and exit of working cylinder$\rho_1 = 999kg/m^{3,}\rho_2 = 1000.1kg/m$^3, pressure of fluid at entrance and exit of working cylinder $P_1 = 1bar$, $P_2 = 25bar$.

From the modified Mechanical Energy Model, it was noted that the Kinetic Energy of the model depends on the fluid's density,$\boldsymbol{\rho_2}$ change in volume,$\Delta\boldsymbol{V}$ and velocity, $\boldsymbol{V_2}$. To obtain these parameters the concept of compressible flow was of importance and the thermodynamic process, isothermal process, experienced by the fluid operation became useful. From the chart in figure 1.2, the relationship between density, and pressure of the system during damper operation is shown. The concept was focussed on the behaviour of the fluid under the parameters analysed i.e. density ($\boldsymbol{\rho}$) and pressure ($\boldsymbol{P}$*)*. The chart further reflected that with a change in pressure came a change in density which was of adherence to the concept of compressible flow. It was noted that the change of density with pressure parameter has not been explored in previous studies,

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henceforth it became the core study in this project. As the process that described the system during operation was that of an *Isothermal thermodynamic*, the chart reflected that the density of the fluid experienced a slight change at high pressures. This further placed emphasis that during damper operation the density of the fluid cannot be taken as being constant, as was the case in previous studies.

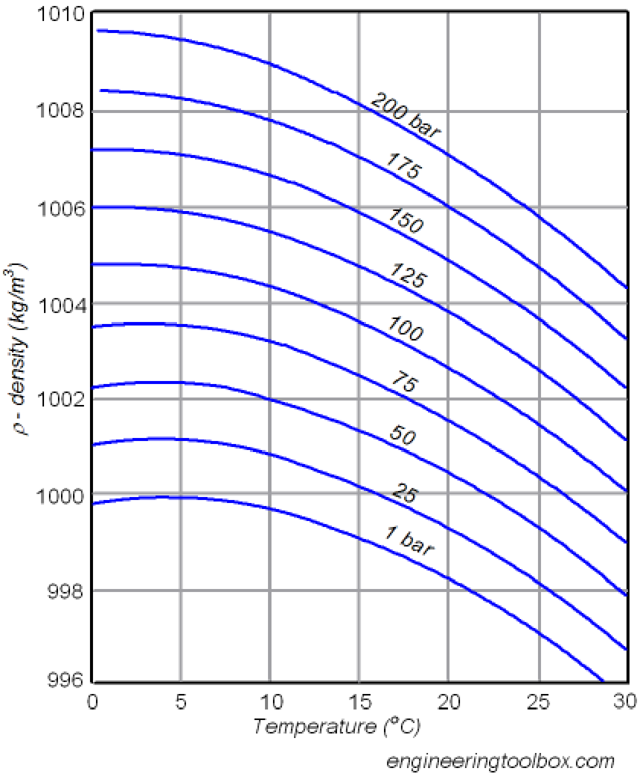

Figure 1.2: Pressure Density Chart of the damper system during operation.

The density,$\boldsymbol{\rho_2}$,and velocity, $\boldsymbol{V_2}$of the Kinetic Energy Model is the density and velocity of the fluid at the entrance of the reserve cylinder. It is at this section where a change in pressure and thus change in density occurs. This point is shown by (c) in the damper diagram and by (d) in the simplified version of the damper system as shown in figure 1.3.

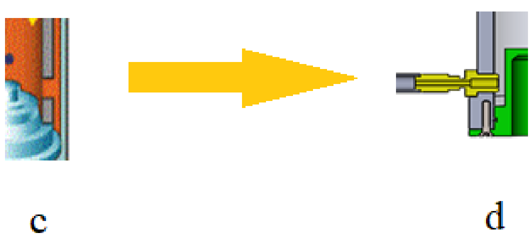

Figure 1.3: Entrance of the fluid to the Reserve cylinder during damper operation.

For the analysis of modelling, the characteristic of the fluid flow between two points of different cross sectional area was considered since the fluid flow during damper operation experiences the same pattern. The following theoretical study related to the fluid flow in figure 1.4.

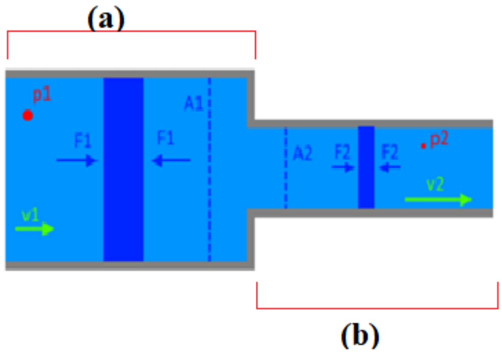

Figure 1.4: Flow of fluid between different areas of the damper system.

With reference to figure 1.4 a study resulted, as per geometry change, in the following:

- A change in cross section, $A_2 < A_1$.
- By the law of conservation of mass, $v_1 < v_2$.
- By Bernoulli equation$p_2 < p_1$.
- By flow continuity principle, $Q_1 = Q_2 = Av$.

Where:A = Cross sectional area of geometry change (m^2),v = Velocity of fluid during operation (m/s),P_1 = Pressure in the pressure cylinder of the damper (Pa), P_2= Pressure in the reserve cylinder of the damper (Pa), $Q_1 = Q_2$ Flow rate of fluid (m^3/s).These changes described the changes of the considered parameters which served as guidance during the Modelling process.

It was observed that the Kinetic Energy increased as the change in volumedecreased. This showed that as a drop in volume occurs due to a drop in the reciprocal of the fluid's density,the fluid during operation travelled from the working cylinder to the reserve cylinder at an increased velocity thus experiencing turbulent flow whereby increased heat is dissipated. This observation was taken to be due to the internal energy of the molecules as they collide at high velocity rates, causing high Kinetic Energies which was dissipated as heat. At a high rate of molecular collisions, higher forces are generated at high velocities. Since the cross sectional area at the entrance to the reserve cylinder was smaller than that at the pressure cylinder, increased fluid turbulence resulted. This increased turbulence generates high internal fluid temperatures which is dissipated. The results hereof was plotted in figure 1.5.

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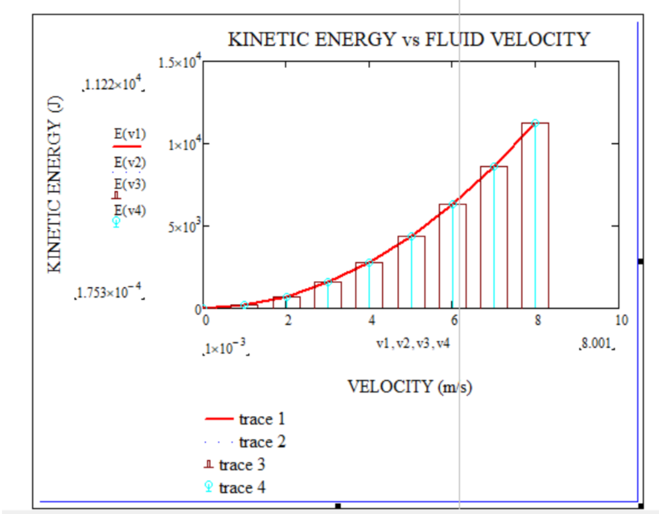

Figure 1.5: Kinetic Energy graph of Modified Model.

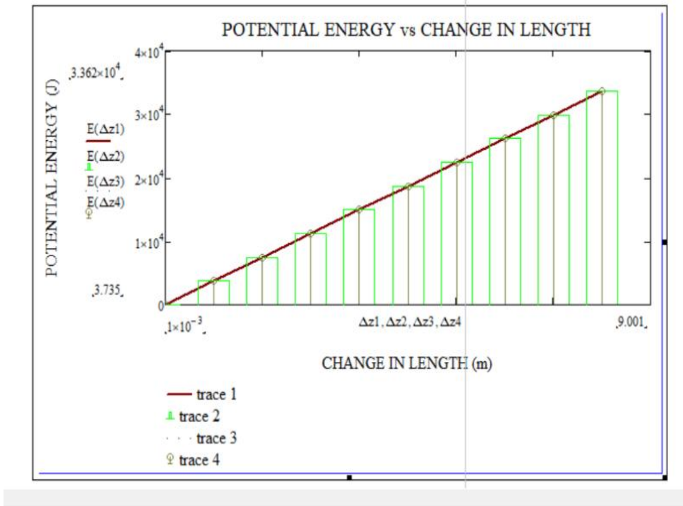

Figure 1.6: Potential Energy graph of model.

The Kinetic Energy graph was plotted and the geometry of the study is shown in figure 4.7. From the graph $\mathrm{E}(v_1)$, $\mathrm{E}(v_2), \mathrm{E}(v_3), \mathrm{E}(v_4)$ represents the Kinetic Energy, shown by the traces, obtained as the fluid's density changes with the respective change in volume caused by change in pressure. A parabolic trend was obtained from the plot of the relation of the Kinetic Energy with respect to change in velocity. This result showed that the principle of compressible flow with focus on the change in pressure and thus change in density of the hydraulic fluid during damping operation can be used to obtain the Kinetic Energy of the damper system which is otherwise wasted through heat dissipation. At any instance during operation the pressure, P_2 can be used to obtain the fluid's density,ρ_2 and thus the velocity, v_2 which is used to obtain the Kinetic Energy of the system during operation. As the Kinetic Energy is dependent on the density,ρ_2 change in volume, ΔV and velocity, v_2, an increase or decrease of these parameters have an impact on the total Kinetic Energy conserved.

For optimal results of the Kinetic Energy, the system's parameters should be analysed when these parameters experience an increase which was obtained during the compression stroke of the damper system. At a fluid density, ρ_2 of 998.80 kg.m^3 and a velocity, v_2 of 0.962m/s the total Kinetic Energy of the damper was 180.71J and at a density, ρ_2 of 998.92 kg/m^3 and velocity of 1.340m/s the Kinetic Energy was 336.7J. This relationship revealed that at higher velocities and increased densities, an increased amount of Kinetic Energy was generated which can be used to power alternative mechanical functions of the vehicle rather than being lost.

With reference to the Modified Potential Energy model of the overall Mechanical Energy model, it was evident that Potential Energy is directly proportional to the height of the hydraulic system i.e. the length travelled by the piston of the Twin Tube damper system.

The geometry of the Potential Energy's graph is shown. From the graph $\mathrm{E}(v_1)$, $\mathrm{E}(v_2), \mathrm{E}(v_3), \mathrm{E}(v_4)$ represent the Potential Energy, shown by the traces, obtained as the fluid density undergoes a slight increase with respective increase in pressure and distance travelled by the damper's piston which is influenced by the magnitude of the force of impact. A linear trend was observed from the plot of the Potential Energy's relation with the respective change in length travelled,ΔZ by the piston. This result showed that at any instance during operation of the damper system, the change in length travelled by the piston influences the fluid's density, of which$\rho_1$increased. By understanding that the Potential Energy is directly proportional to the density, change in volume, gravitational acceleration and change in distance travelled by the piston- An increased change in the distance travelled by the piston caused an increase in the total Potential Energy. For optimal results the Potential Energy was obtained when the piston experiences a small travel distance since this allowed a large pressure difference thus increased Potential Energy. This result further revealed that the application of compressible flow is relevant as this concept was used to analyse the magnitude of the density and pressure during operation which in turn was used to obtain the change in length travelled by the piston. For interpretation of the damper's potential to conserve Energy, at a change in length of 0.25m a total Potential Energy of 95.855J was generated and at a change in length of 0.11m a total Potential Energy of 400.0J was generated. This observation revealed that as the piston got displaced the damper system generated Energy which can be used rather than dissipated during damper operation.

By studying the fluid's compressibility, during the compression stroke of the system, it was noted that as the system experienced an increase in pressure due to the impact force, the density at this pressure change also experienced a change. The increase of the fluid's density

during operation is small and so is the change in volume of the system. This is because at the point of impact force, the force at which impact was experienced caused a slight increase in the system's pressure hence a slight increase in pressure causes a slight increase in the fluid's density, since density during

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compressible flow at constant temperature is directly proportional to the pressure- With this knowledge and with reference to the parametric experimental results it was analysed that higher density magnitudes was achieved when the system experienced high pressure increases. In the system's measurable density, pressure and change in volume, it was revealed that the system's compressibility was accounted for in the total conservable Potential and Kinetic Energy. Henceforth as the system experienced an increase of pressure at any given force, the density measured at that instant and the change in volume was used for calculating the Potential and Kinetic Energy. As these parameters increased, the system's total conservable energy also increased, resulting in the analyses that the system's total Conservable Energy is dependent on the quantity of the system's pressure (***P***), density ($\boldsymbol{\rho}$) and velocity (***V***).

SIMULATION RESULTS.

Fluid Pressure Analysis:

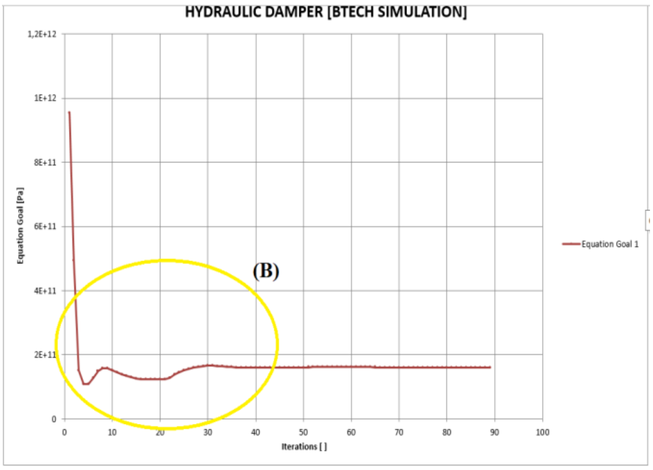

Figure 1.7: Pressure Simulation Results.

From the pressure simulation results, it was observed that the pressure difference between iterations 0-5(t) showed a large drop and from iterations 5-40(t) the pressure experienced fluctuations of maximum and minimal peaks until it stabilized, as shown by the encircled area marked **B**. By studying the geometry of the damper system and fluid behaviour during damping operations, the drop in the pressure can be caused by the resistance of fluid flow inside the damper system. This resistance is caused by the change in geometry between the working cylinder and reserve cylinder as the fluid experienced change in velocities thus experienced turbulence as it entered and exit the change in geometry of the damper from the working cylinder to the reserve cylinder. This resulted in a pressure drop since pressure drop during turbulence is proportional to the square of the velocity (P αV^2). The cylinder's wall roughness **(ε)** also contributed to the pressure drop since the roughness effects the drag of the fluid where the drag between the fluids layers shears them apart, due to the viscous force F_v and inertial forceF_i, hereby resulting in each layer travelling at different speeds. As the fluid layers travelled at different speeds it experienced turbulent flow which produced eddies that moved randomly inside the damper as the fluid entered and exit the reserve cylinder. During this occurrence the fluid experienced a transition from laminar to turbulent flow.

All this resistance during the initial movement of the piston was high and had to be overcome by the fluid for the damper to perform its function effectively- Thus during the first iterations the drop was large and thereafter became minimal as the fluid overcome the resistance whilst operating. From iterations 5-40(t) the drop fluctuated and experienced a smaller drop as the fluid in motion overcome the initial high resistance and thus stabilized at small impact forces.

Fluid Velocity Analysis:

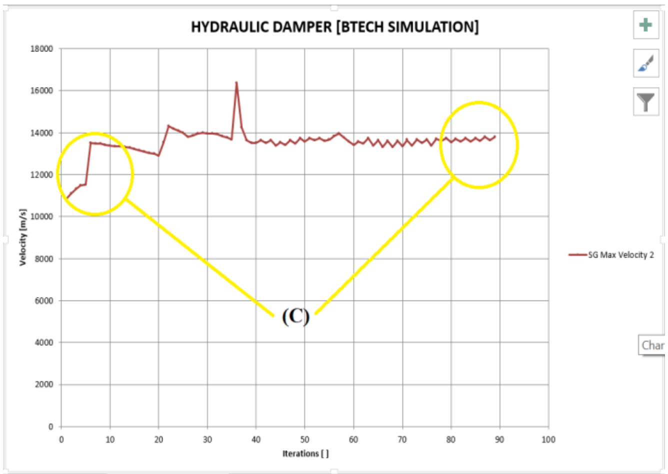

Figure 1.8: Velocity Simulated Results.

The geometry of the velocity simulation result showed an increase and decrease to a very high peak at approximately 35-40(t), this showed that during this iteration the damping was rough. This region is the same region of analysis as the pressure drop, meaning, as discussed, that the fluid during operation experiences high turbulence and an increased rate of velocity as the fluid travelled through the change of geometry as it enters and exits the reserve cylinder during operation. Since the change in geometry of the reserve cylinder as compared to the working cylinder allows a smaller area, A_2 thus increased velocity, v_2 i.e. $(v_2/\alpha\, A_2)$. Both these factors has an impact on the fluctuating pattern of the increasing velocity. The high peaks, shown by encircled area marked **C**, could be caused by the harsh impact during operation. This meant that the impact force (F) which the vehicle hits the pothole is directly proportional to the velocity (V) at which the piston travels i.e. (FαV), this influenced the fluid's velocity during operation. Since the drop in pressure of the system is proportional to the square of velocity, the drop in pressure due to the increase in average speed was interpreted as the transfer of Kinetic Energy from the random molecular motion to the mean motion. As the fluid flowed through the constricted passage of the reserve cylinder, it accelerates resulting in an increased Kinetic Energy.

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Fluid Density Analysis:

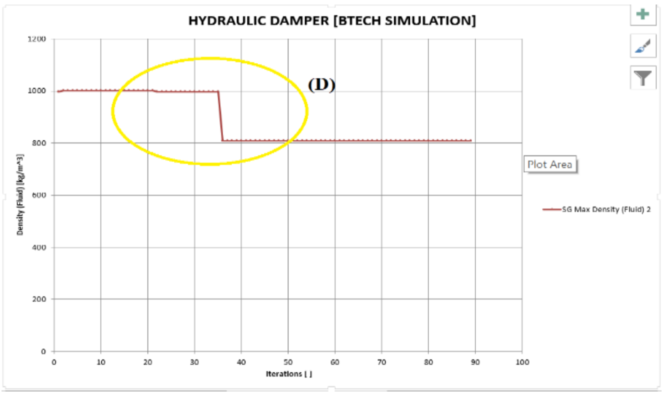

Figure 1.9: Density Simulated Results.

In compressible flow, under an isothermal thermodynamic process, the density of the fluid is directly proportional to the pressure (Pαρ). As the system dampens vibratory oscillations during impact the system experiences a drop in pressure between iterations 0-40(t). This drop results a decrease in the fluid's density, hereafter the density stabilizes. The density of the fluid is less dense during iterations 40-90(t) compared to iterations 0-30(t), this trend follows the same trend of the system's pressure.-When the system experiences high pressure, P_1 the density of the fluid is more dense, ρ_1 and when the pressure is low, P_2 the density is less dense, ρ_2. The behaviour of the density is dependent on the system pressure as adherence to the principle of compressible flow. Hence with the fluctuation in density the Kinetic Energy also fluctuates. This region of density change is shown by the encircled area marked **D** in the results plot.

Fluid Turbulent Energy Analysis.

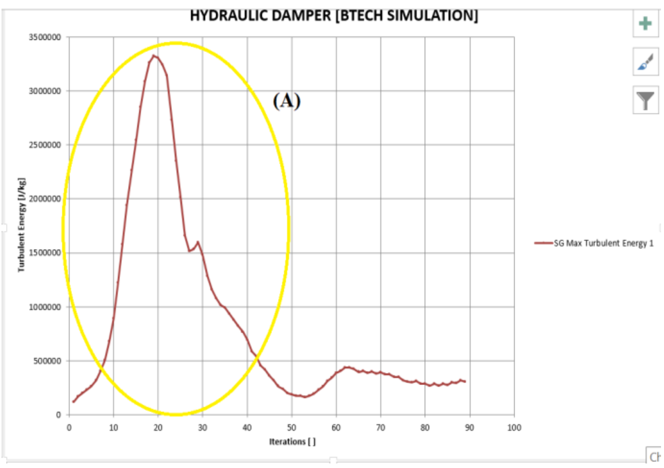

Figure 1.10: Turbulent Energy Simulated Results.

Fluid turbulence is the violent and unsteady movement of a fluid. By interpretation of the damping system, during operation, results in high turbulent Energy during iteration 0-40(t) of which hereafter it slightly fluctuates until it stabilizes. Now the iteration 0-40(t) represents the system's action area and by theoretical study it is during this initial motion of the fluid as it enters and exits the reserve cylinder that the fluid experiences high resistance. As the system operates and while the fluid overcomes the resistance turbulent flow is experienced. The turbulent flow result in eddying motion of molecules of the fluid henceforth a large part of the Mechanical Energy goes to the formation of these eddies which eventually results in energy dissipated. The turbulent Energy produced shown by the encircled area marked **A** is characterized by the unsteady eddying motion of the molecules. These eddies are in constant motion with respect to each other, at any instant the magnitude of the eddies resulted in fluctuations in the pressure and velocity flow of the fluid and according to the streamline trend of the velocity result it was observed that at high velocities the eddies interact with each other as they move thus resulting in exchange and transfer of energy. The turbulent Energy is at peak during iteration 0-40(t) because it is during this action phase that the system experiences high turbulence and thus having high Energy dissipation which can be conserved.

Analysis:

The results revealed that there was a correlation between the theory of study and the application hereof. From observation of the schematics it was noted that the parameters i.e. fluid density and fluid velocity, not only experienced change due to change in fluid pressure but these parameters also experiences change due to a change in geometry between the pressure cylinder and reserve cylinder. Through simulation it was revealed that due to change of damper geometry, the parameters experienced an increased change which resulted in an increased potential of the damper's conservable Energy. The Kinetic Energy of the system varied from 180-366J and the Potential Energy varied between 95.83-400.0J. This showed that the quantity of the generated energy could be used to power other auxiliary functions of the vehicle i.e. the quantity of conserved Energy could be used to contribute to the Energy required by the flywheel of the vehicle. This can result in the potential of the damper system to minimize fuel consumption hereby contributing to the sustainability of Energy.

CONCLUSION AND RECOMMENDATION:

Based on the obtained results, it was concluded that the force at which the vehicle hits a bump impacts the damper system's potential to generate Energy. At high impact forces higher fluid pressures was observed which resulted in higher quantities of generated Energy. It was also observed that during an increase in fluid pressure, the density of the fluid varied proportionally which also contributed to the system's potential to generate

Energy. The models: $E_p = \rho_1(\Delta V)(g)(\Delta Z)$ and $E_k = \frac{1}{2}[\rho \Delta V] * V^2$ were the models selected that described the damper system's Kinetic and Potential Energy during operation. It was analysed that since the system's Mechanical Energy ranged from 180-400.0J, this Energy which is dissipated and wasted can be used to power other Mechanical systems of the vehicle.

The success of this project revealed that the fluid in a Twin Tube damper system, during damper operation, can be described by the concept of Compressible Flow. Thus the compressibility potential of the fluid can be considered in the process of developing future models related to damper systems i.e. damper performance characteristic models. Furthermore for analysis purposes the function ((log_e) should be studied in detail to understand the correlation it has with the system's Energy potential. For contribution towards the sustainability of Energy, analysis can be made to investigate which mechanical systems can be powered by the conserved Energy under different damper operations which can help in selecting suitable Regenerative technology that can harvest the quantity of Energy obtained from damper systems.

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