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Modeling and simulation of energy harvesting hydraulically interconnected shock absorber

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Abstract: Ride comfort, road handling and fuel efficiency of a vehicle have always been crucial factors during vehicle shock absorber design. This paper proposes and studies a novel energy harvesting hydraulically interconnected shock absorber (EH-HISA) system to improve energy harvesting and ride comfort. A comparison study is done for the dynamic responses and power harvested by the vehicle equipped with EH-HISA and previous design for energy-harvesting hydraulically interconnected suspension (EH-HIS). In addition, the EH-HISA consists of two energy harvesting units compared to four energy harvesting units in EH-HIS, thus reducing the cost and weight of the overall system. A full car model is set up in AMESim to simulate the vehicle over a C class road. The comparison indicates that EH-HISA shows 11% reduction in lateral acceleration of car body center of gravity, during double lane change test over EH-HIS. While the peak roll angle of the vehicle body shows almost similar results of 1.4 degrees for EH-HISA and 1.2 degrees for EH-HIS. The average energy harvested for EH-HISA reaches a maximum value of 230 W and shows an improvement of 222 % over EH-HIS for the same road conditions and vehicle parameters.

Keywords: Energy harvesting, Interconnected suspensions, Hydraulic suspension, Vehicle dynamics, Ride comfort, Double lane change test

1. INTRODUCTION

Majority of vehicle suspension systems consist of dampers and springs in parallel to minimize the vibrations in the car body due to the road surface. In addition, the function of the suspension is to maintain tire ground force for reliable handling, comfort and stability of the vehicle. In traditional dampers, the vibration energy from the road surface gets converted into heat due to friction in the viscous oil which gets dissipated. There is good potential to harvest this energy by converting it into electrical energy which can be used by the vehicle or stored in the battery. Much research has been done to harvest this energy by converting the traditional wasted energy into electricity.

Xie et al. (2015) developed a dual-mass piezoelectric bar harvester to harvest ambient vibration energy of a vehicle suspension system. Zhang et al. (2017) proposed an electro-hydraulic energy harvesting damper, using unidirectional generators to improve energy harvesting efficiency. Zhou et al (2020) introduced a magnetic energy harvesting suspension that provides high vehicle safety in a compact structure. However, the result of harvested peak power is low. Zhou et al. (2013) created and modeled a type of rational electromagnetic regenerative damper consisting of mechanical motion rectifier. Abdelkareem et al. (2018) presented a comparison paper that includes most of energy regenerative suspensions research from the 1900s to present.

In order for energy harvesting suspension to be utilized in the real world, the suspension also needs to provide great handling performance and ride comfort. Mercedes-Benz developed an active body control suspension system that will keep the car level during strong acceleration and braking by charging or discharging the hydraulic oil inside the hydraulic damper. However, active suspensions can be costly and unreliable. Qi et al. (2020) proposed a novel suspension with both hydraulically interconnected suspension and electronic controlled air spring. This design obtained high performance for both handling stability and ride comfort.

Chen et al. (2019) modeled and validated a novel hydraulic interconnected suspension combined with energy harvesting shown in Fig. 1. Later, this Energy harvesting hydraulic interconnected suspension (EH-HIS) was modeled, built and tested by Qin et al. (2022). The EH-HIS system exhibits 60% and 11% improvements in the anti-rolling and anti-pitching performances over the traditional suspension during emergency steering and braking maneuvers. The average harvested power of the sub-module reaches 82 W at the excitation of 2 Hz frequency and 20 mm amplitude, while the full-size SUV equipped with the EH-HIS can obtain 215 W and 525 W average power on D-class road with a driving velocity of 60 km/h and 80 km/h, respectively. However, the EH-HIS system still has room for improvement. This research paper proposes a novel design of a hydraulic energy harvesting interconnected shock absorber (EH-HISA) system and compares it with the EH-HIS. The proposed novel design for the interconnected energy harvesting system consists of a hydraulic cylinder mounted in parallel with a spring in the vehicle suspension system. The EH-HISA consists of two energy harvesting units as compared to four energy harvesting units in EH-HIS, thus reducing the cost and weight of the

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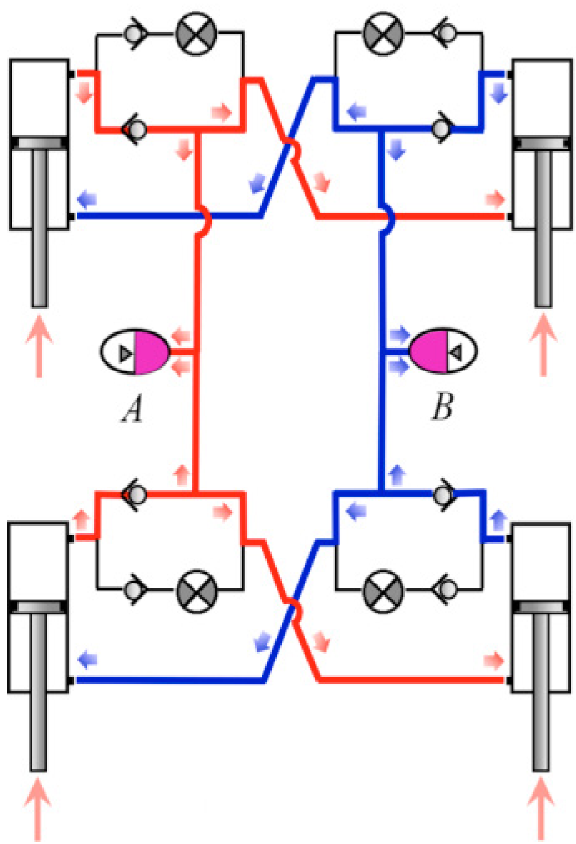

Figure 1. Energy-harvesting hydraulically interconnected suspension studied by Qin et al. (2022)

overall system. For comparison with the EH-HIS, simulation model is set up in Siemens AMESim software.

This paper is organized as follows. The design and working principle of EH-HISA is presented in section 2. Section 3 explains the simulation model setup and lists the parameters of the vehicle and hydraulic system. The results of the full car model double lane change test simulation and energy harvesting simulation are analyzed in section 4. The conclusion of the paper is discussed in section 5.

2. DESIGN AND WORKING PRINCIPLE

2.1 Overall design

The novel EH-HISA design consists of a hydraulic cylinder mounted in parallel with a spring in the vehicle suspension system. The interconnected hydraulic system consists of four hydraulic cylinders, sixteen check valves, four accumulators and two energy harvesting units. The energy harvesting unit comprises the hydraulic motor and gearbox coupled to a generator and the corresponding electric circuit. Two different closed hydraulic circuits are formed by connecting the diagonally opposite cylinder with each other. Each circuit consists of an energy harvesting unit and two accumulators (high pressure and low pressure) on either side of the energy harvesting unit. The diagonal connection of the cylinders ensures flow to both the energy harvesting units in pitch as well as roll motion of the vehicle. The working modes of the EH-HISA are bounce motion, roll motion and pitch motion, illustrated in Fig. 2(a), Fig. 2(b) and Fig. 2(c) respectively.

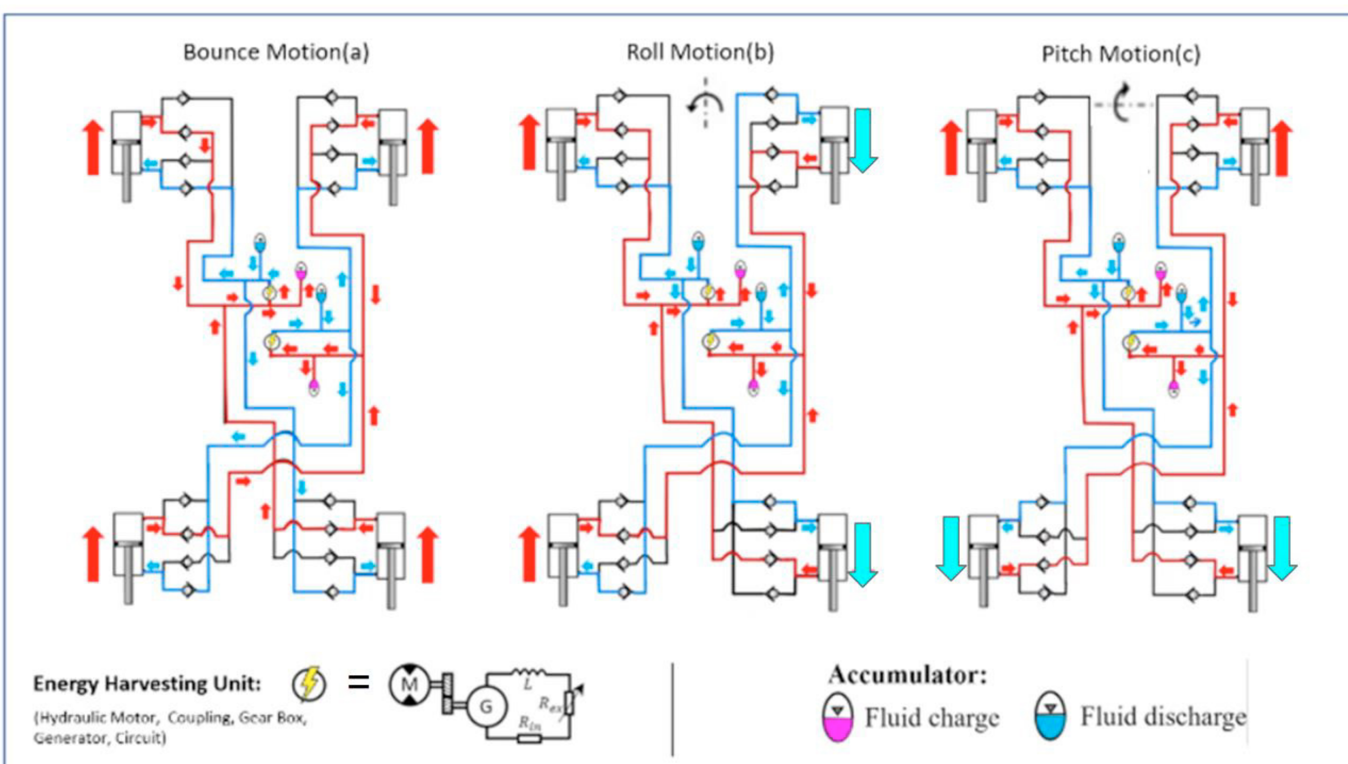

Figure 2. Working modes of the novel EH-HISA during bounce motion (a), roll motion (b) and pitch motion (c) of vehicle

2.2 Bounce Motion

Vehicle under bounce motion is presented in Fig. 1(a). During bounce motions, all four cylinders of the suspension are compressed. The oil flows from the top chamber of the cylinders through the two hydraulic motors into the lower chambers of the diagonally opposite chamber. The accumulators provide oil supply to reduce the fluctuation in the flow. The flow through the hydraulic motors coupled to the generator results in production of electric energy.

2.3 Roll Motion

Fig. 1(b) illustrates the working mode under roll motion. During turning, the vehicle tilts towards one side causing roll motion. In roll motion, the outer cylinders are compressed, and the inner cylinders are extended. This results in the flow of oil from the high-pressure chamber of the hydraulic cylinder to the respective hydraulic motors. This high-pressure fluid passes through the hydraulic motor and flows into the low-pressure chamber of the diagonally opposite cylinder. The inertia of the hydraulic motor slows down the extension and contraction of the hydraulic cylinders, thereby providing better anti-rolling performance.

2.4 Pitch Motion

The vehicle motion during braking conditions results in compression of the front two cylinders and extension of the rear two cylinders. This results in pitching motion of the vehicle body. The high-pressure fluid from the upper chamber of the front two cylinders passes through the hydraulic motors into the lower chambers of the diagonally opposite cylinders. The inertia due to the hydraulic motor restricts the flow in the hydraulic lines and thus helps in improving vehicle dynamics.

3. SIMULATION MODEL SETUP IN AMESIM

3.1 Full Car Model

First, the hydraulic circuit model is set up for the EH-HISA system. Fig. 3 shows the hydraulic circuit of the EH-HISA system. The hydraulic circuit model comprises two diagonal hydraulic circuits each of which consists of two hydraulic cylinders, two accumulators, eight check valves and one energy harvesting unit. The hydraulic cylinders are connected in parallel to the spring and to the vehicle chassis and wheels in the full car model.

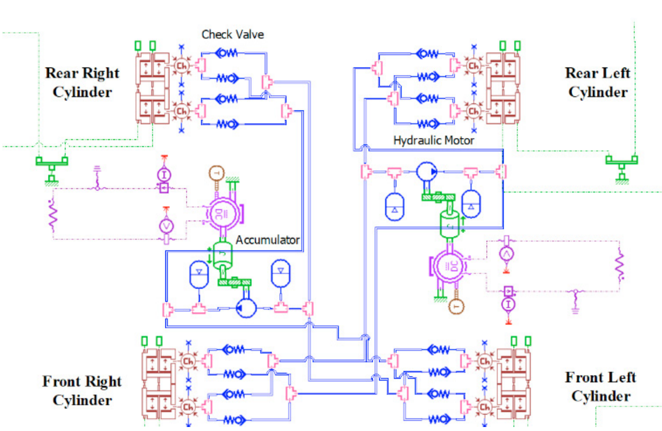

Figure 3. Hydraulic circuit Model setup in AMESim

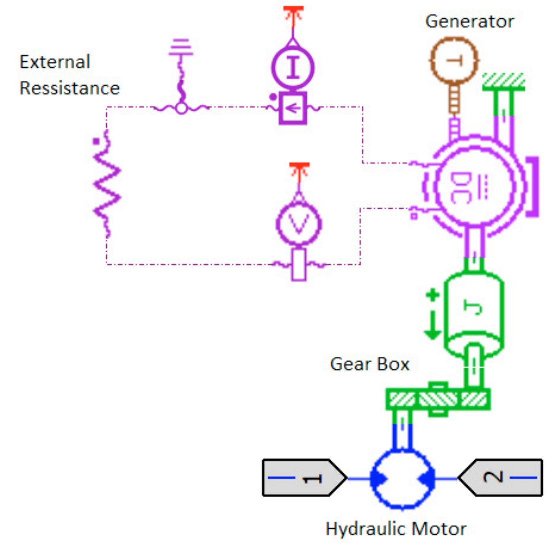

Figure 4. Energy harvesting unit of EH-HISA

The energy harvesting unit shown in Fig. 4 comprises the hydraulic motor, gearbox, electric generator and external electric circuit. The external resistance in the electric circuit is the total equivalent resistance of the battery that needs to be charged. The gear ratio is set at 0.25 where the speed of rotation is multiplied from hydraulic motor to the generator.

A SUV vehicle is selected for simulation as a larger vehicle can potentially harvest more energy and off-road driving conditions are favorable for interconnected suspension systems (Abdelkareem et al., 2018). Vehicle parameters are calculated using CarSim software for practical simulation conditions. Table. 1 lists the parameters of the vehicle used for simulation.

Table 1. Vehicle Parameters

Parameter	Value	Unit
Sprung Mass	2257	kg
Unsprung Mass (Front)	125	kg
Unsprung Mass (Rear)	150	kg
Moment of Inertia (Roll)	846.6	kg*m*m
Moment of Inertia (Pitch)	3524.9	kg*m*m
Moment of Inertia (Yaw)	3524.9	kg*m*m
Suspension Spring Stiffness	180000	N/m
Suspension Damping Coefficient	3800	N/(m/s)
Wheel Spring Stiffness	440000	N/m
Wheel Damping Coefficient	100	N/(m/s)
Front Axle Height	400	mm
Rear Axle Height	425	mm
Front Track	1725	mm
Rear Track	1750	mm

Using these vehicle parameters, a full car model is set up in AMESim as shown in Fig. 5. The full car model is equipped with the complete energy harvesting hydraulically interconnected suspension (EH-HISA) system including both sets of hydraulic circuits and all four hydraulic cylinders. The hydraulic circuit of EH-HISA is modeled in the subcomponent block as show in Fig. 5.

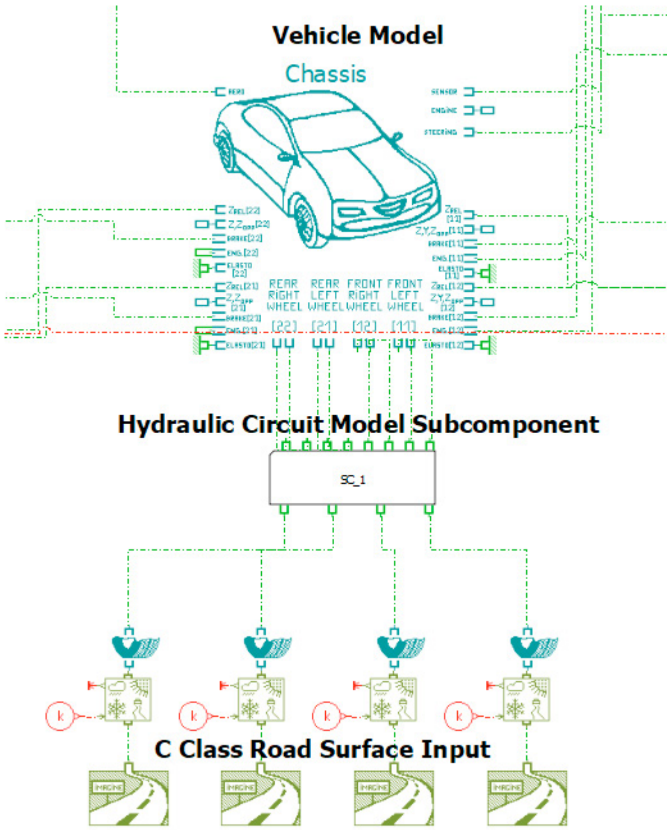

Figure 5. Full car model setup in AMESim

3.3 Hydraulic parameter optimization

All hydraulic parameters need to be sized as they can greatly affect the performance of the EH-HISA. The hydraulic system consists of 3 important components: double-acting cylinders, hydraulic motor and accumulators that need to be sized for efficient working of the shock absorber system.

The hydraulic cylinder sizing consists of 3 parameters, the piston diameter, the rod diameter and the piston stroke length. For the purpose of simulation, the piston diameter, rod diameter and stroke length are set at 50.80 mm, 19.05 mm and 178 mm respectively.

The hydraulic motor sizing involves calculating the capacity of the hydraulic motor while making sure that the motor is running in its most efficient speed range. Hydraulic motor with capacity of 20 cc/rev is selected for simulation as the typical average flow rate of the EH-HISA system is 10 LPM and the 20 cc/rev hydraulic motor satisfies its most efficient speed range at this flow rate. The hydraulic accumulator also has 3 important sizing parameters: the accumulator volume, the pre charge pressure and the working pressure. Typically, the volume of the accumulator should be enough to contain the amount of fluid in half of the hydraulic cylinder chamber. (Chen et al., 2019)

Another important parameter that needs to be considered is the external resistance in the electrical circuit. The external resistance can greatly affect the damping of vibrations to the vehicle as the inertia of the hydraulic motor depends on the external resistance.

Since there are various variables that need to be tuned while calculating the optimal parameters, a *Non-Linear Programming by Quadratic Lagrangian* (NLPQ) optimization algorithm is used. The RMS value of acceleration of the car body center of gravity is selected as the objective function to be minimized as improving ride comfort is the primary function of the EH-HISA.

The NLPQ algorithm is used, and the optimization process is realized in AMESim software. The optimization parameters are listed in Table 2.

Table 2. Optimization parameters and ranges

Parameter	Value/Range	Unit
Car Body Acceleration (Obj. Fn.)	-	m/s/s
Step Size	0.01	N.A.
Accuracy	0.01	N.A.
Accumulator volume	0.1-1.0	L
Accumulator working pressure	10-30	bar
Accumulator Pre-charge pressure	5-28	bar
External Resistance	5-20	ohm

After running a few iterations of optimization, a set of hydraulic parameters are selected for further simulation. The final optimized parameters are listed in Table 3.

Table 3. Selected hydraulic parameters for simulation

Parameter	Value	Unit
Accumulator volume	0.17	L
Accumulator working pressure	12.8	bar
Accumulator Pre-charge pressure	7.5	bar
External Resistance	6	ohm

4. SIMULATION RESULTS

4.1 Double lane change test results

For the full car model, a random C class road surface is generated in AMESim. The vehicle is simulated for double lane change maneuver with the constant speed of 50 kmph over the C class road surface. All the hydraulic and vehicle parameters mentioned in section 3 are considered. Fig. 6 shows the steering wheel angle input in degrees for the double lane change test.

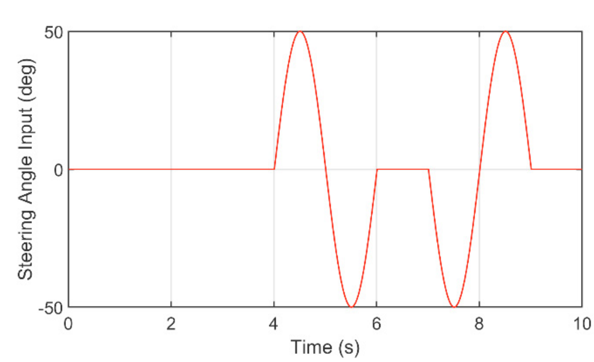

Figure 6. Steering angle input in deg for double lane change test

The lateral acceleration of the car body center of gravity is studied from the simulation as the main aim is to minimize this acceleration to improve ride comfort. The roll angle of the vehicle is also plotted to determine the extent of body rolling during vehicle motion. Fig. 7 shows the lateral acceleration of the car body center of gravity during double lane change test simulation.

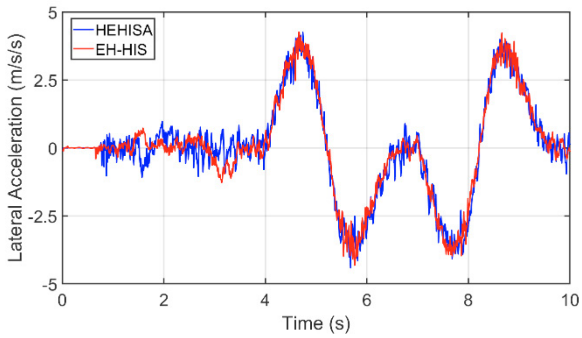

Figure 7. Lateral acceleration of car body COG comparison

It can be observed from Fig. 7 that the lateral acceleration of car body COG is almost similar in the case of EH-HISA and EH-HIS. In both the cases, the peak acceleration during double lane change test does not exceed 4 m/s/s and provides favorable riding comfort. In order to evaluate the extent to which the EH-HISA performs better than the EH-HIS, the RMS value of lateral acceleration is calculated. The RMS lateral acceleration of car body COG is 1.61 m/s/s and 1.81 m/s/s for EH-HISA and EH-HIS respectively. Thus, the EH-HISA reduces the lateral acceleration of car body COG by 11% compared to EH-HIS.

Fig. 8 shows the roll angle of the vehicle equipped with EH-HISA and EH-HIS during the double lane change test simulation.

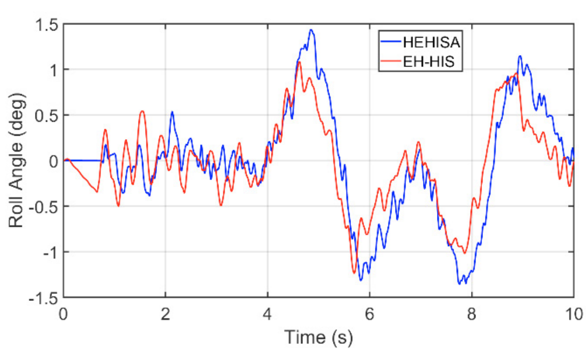

Figure 8. Roll angle of car body COG comparison

The results from Fig. 8 shows almost similar anti-rolling performance for EH-HISA and EH-HIS. The peak value of roll angle during the double lane change test simulation does not exceed 1.4 and 1.2 degrees for EH-HISA and EH-HIS respectively. The EH-HIS shows better anti rolling performance because of the higher damping force provided by the accumulator during the primary stroke of the hydraulic cylinder.

4.2 Energy harvesting simulation results

EH-HISA can harvest vibration energy while ensuring the dynamic response of the vehicle. The full car model is simulated for motion in a straight line over a C class random road surface and the average values of voltage and current in the electric circuit are calculated. The average voltage and current generated in a single energy harvesting unit during simulation of EH-HISA and EH-HIS is found out to be 24.02 V, 9.45 A and 4.80 V and 1.89 A respectively. Also, the calculated total power harvested by EH-HISA and EH-HIS taking into account the number of energy harvesting units in both of them: 2 in EH-HISA and 4 in EH-HIS is 230.59 W and 71.44 W respectively for EH-HISA and EH-HIS.

The EH-HISA harvests almost two times the power harvested by EH-HIS for the same vehicle and simulation parameters. Thus, the EH-HISA performs significantly better in energy harvesting as compared to EH-HIS. This is because the EH-HISA harvests energy in both the extension as well as compression stroke of the hydraulic cylinder. Whereas the EH-HIS harvests energy only during the rebound stroke and charges the accumulator during the primary stroke.

4.3 Overall performance calculation

Table 5 lists the overall performance (lateral acceleration, roll angle and energy harvested) of the optimized EH-HISA while comparing it with the previous design of EH-HIS.

Table 5. Overall performance (lateral acceleration, roll angle and energy harvested) comparison

Title	EH-HISA	EH-HIS	% Improvement
Lateral Acceleration	1.60 m/s/s	1.81 m/s/s	11.60 %
Peak Roll Angle	1.4 deg	1.2 deg	-16.66 %
Total power harvested	230.59 W	71.44 W	222.76 %

Thus, the EH-HISA performs better than the EH-HIS in reducing lateral acceleration and significantly better in energy harvesting. Although it performs worse in the case of peak roll angle during double lane change test simulation.

5. CONCLUSIONS

A novel hydraulic energy harvesting interconnected shock absorber is proposed in this paper to improve efficiency of energy harvesting, ride comfort and road handling performance. The shock absorber design consists of two energy harvesting units that harvest energy during both the extension/compression and rebound stage of the shock absorber. A full car model is set up in AMESim software with vehicle parameters of a general SUV. The hydraulic parameters are calculated using the nonlinear programming by quadratic lagrangian optimization algorithm with the objective function to minimize the car body acceleration.

The full car model equipped with EH-HISA and EH-HIS are simulated over a C class random road surface. Double lane change test is simulated, and the car body COG lateral acceleration and vehicle roll angle are plotted. The EH-HISA is found to have better ride comfort performance as compared to EH-HIS. The reduction in car body COG lateral acceleration during double lane change test is found to be 11 %. The peak value of roll angle during the double lane change test simulation does not exceed 1.4 and 1.2 degrees for EH-HISA and EH-HIS respectively.

The full car model simulation is done for power harvested by the vehicle during simulation on a C class random road surface. The vehicle motion is simulated in a straight line with a speed of 50 kmph. The average power harvested is compared for EH-HISA and EH-HIS and it is observed that EH-HISA harvests 230.59 W whereas EH-HIS harvests 71.44 W. The EH-HISA harvests 222.76 % more power than the EH-HIS for the same vehicle and simulation parameters.

Overall, the EH-HISA appears to perform better than the EH-HIS in energy harvesting, and riding comfort. Another advantage of EH-HISA over EH-HIS is the reduced number of energy harvesting units. Thus, reducing the overall cost and weight of the system. Lab bench tests and practical implementation will be the next research plan.

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REFERENCES

Abdelkareem, M. A., Xu, L., Ahmed Ali, M. K., Elagouz, A., Mi, J., Guo, S., Liu, Y., and Zuo, L. (2018). Vibration energy harvesting in automotive suspension system: A detailed review, *Applied Energy*, vol. 229, pp. 672-699.

Chen, Y., Qin, B., Guo, S., Yu, L., & Zuo, L. (2019). Asymmetric Energy Harvesting and Hydraulically Interconnected Suspension: Modeling and Validations. *Proceedings of the ASME 2019 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference. Volume 3: 21st International Conference on Advanced Vehicle Technologies; 16th International Conference on Design Education.* Anaheim, California, USA. August 18–21, 2019. V003T01A009. ASME.

PETRÁNY, M. (2019). The Secret Behind Mercedes' Magically Plush Ride. *Road and Track*.

Qin, B., Chen, Y., Chen, Z., Zuo, L. (2022). Modeling, bench test and ride analysis of a novel energy-harvesting hydraulically interconnected suspension system, Mechanical Systems and Signal Processing, Volume 108456, ISSN 0888-3270, https://doi.org/10.1016/j.ymssp.2021.108456.

Qi, H., Chen, Y., Zhang, N., Zhang, B., Wang, D., & Tan, B. (2020). Improvement of both handling stability and ride comfort of a vehicle via coupled hydraulically interconnected suspension and electronic controlled air spring. Proceedings of the Institution of Mechanical Engineers, *Part D: Journal of Automobile Engineering*, 234(2–3), 552–571. https://doi.org/10.1177/0954407019856538

Xie, X.D., Wang, Q. (2015). Energy harvesting from a vehicle suspension system. *Energy*. 385–392.

Zhang, Y., Chen, H., Guo, K., Zhang, X., Li, S.E. (2017). Electro-hydraulic damper for energy harvesting suspension: Modeling, prototyping and experimental validation, *Applied Energy*, Volume 199, Pages 1-12.

Zhou, L., Zuo, L., Kuang, J., and Luhrs, G. (2013). Energy-harvesting shock absorber with a mechanical motion rectifier. *Smart Materials and Structures*, vol. 22, no. 2, 2013.

Zhou, Ran & Sun, Feng & Yan, Mingyin & Jin, Junjie & Li, Qiang & Xu, Fangchao & Zhang, Xiaoyou & Nakano, Kimihiko. (2020). Design, analysis and prototyping of a magnetic energy-harvesting suspension for vehicles. Smart Materials and Structures. 29. 10.1088/1361-665X/aba538.