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Design and Analysis of Regenerative System in Shock Absorber

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ABSTRACT

The energy source of vehicles is changing rapidly and significantly in recent years with the increase in renewable energy technologies especially in the case of electric vehicles (EVs). A smart solution has emerged in which the wasted energy in a vehicle's shock absorber is converted to an alternative energy for the cars themselves, and this is called an energy regenerative shock absorber. Whereas existing regenerative shock absorbers mainly focus on the methods of energy harvesting, there is no such regenerative shock absorber for use in extended range EVs. In this project, we present a novel high-efficiency energy regenerative shock absorber using super capacitors that is applied to extend the battery endurance of an EV. A renewable energy application scheme using regenerative shock absorbers for range extended EVs is designed. This system collects the wasted suspension power from the moving vehicle by replacing the conventional shock absorbers as these energies are normally dissipated through friction and heat.

Keywords: *Electrical vehicles, rack and pinion, regenerative shock absorber*

INTRODUCTION

Electric vehicles (EVs) are considered to be a clean and effective solution with respect to the fossil fuel crisis and excessive emissions of carbon dioxide (CO2). The United States, Europe, China and Japan have led policymakers and the automobile industry to seek alternative fuels and to improve energy efficiency for transportation through the development of EVs. However, the development and application of battery electric vehicles (BEVs) has long been obstructed by their extremely limited mile range due to limitations of materials, capacity, reliability and consistent characteristic of the battery systems, which is referred to as ''range anxiety". The solutions focus on battery management strategies (BMS), fast charging and charging station site selection . These solutions could be summarized as energy conservation methods for applications in extended range EVs. As another solution, a number of studies focusing on energy harvesting and alternative energy sources may be a better and more thorough solution.

The shock absorber is a key component of the vehicle suspension and is combined with the suspension spring to filter vehicle vibration when driving on rough roads. Typically, energy from vibration sources is dissipated through hydraulic friction and heat in shock absorbers. To reduce the energy cost of vehicles, the energy wasted in the shock absorbers has been investigated and characterized in several studies. Fundamental research has examined and analyzed the feasibility of harvesting energy from the shock absorber since the 1980s, and a regenerative shock absorber was proposed to harvest the kinetic energy dissipated by the suspension vibration in the shock absorber. In the literature, Segel et al. described [1]

and analyzed how energy lost in a car shock absorber corresponding to different vehicles' speed and road roughness. Karnopp inspected the possibility of replacing the hydraulic shock absorber with electromagnetic damping using a permanent magnetic motor and variable resistors. This study indicated that an electromagnetic damper is practicable though the performance of response time is degraded. Recent studies further uncovered the potential of energy harvesting from the shock absorber. Abouelnour and Hammad simulated a regenerative electro mechanic suspension based on a quarter car model and predicted that a maximum power of 150W can be harvested at 90 km/h. Zuo also made a significant improvement in the energy harvesting and ride comfort of regenerative vehicle suspensions over existing techniques. They presented a regenerative shock absorber and estimated a power range of 100–400W at 100 km/h depending on the road profile. Huang et al. proposed an analytical methodology based on ground–tire interface analysis and ride comfort cost function for an energy-regenerative suspension design. This research work aimed to achieve optimal performance and ride comfort and derive the closed-form solutions of the performance metrics for an energy-regenerative suspension. Among these initial theoretic studies, the shock absorber was transformed into an energy harvesting device from an energy dissipating device. Possible noise and heat in the conventional working progress are eliminated, which is environmental friendly and lifetime extending. Under the previously basic theory of suspension energy harvesting, some further studies about the design and optimization of a regenerative shock absorber have been conducted. With respect to long-term evolution and development, regenerative shock absorbers can be classified into three categories based on their working principles: electromagnetic, hydraulic and mechanical designs.

The first category directly uses an electromagnetic method to generate the electric power including linear and rotary schemes. A linear electromagnetic regenerative shock absorberconverts the kinetic energy of vertical oscillations into electricity by electromagnetic induction. The structure of linear schemes is simple and kinetic energy is converted directly. Zuo et al. designed and characterized the widely used linear electromagnetic shock absorber in Finite element and theoretical models were analytically optimized the magnetic field in the linear electromagnetic shock absorber. Zhang et al. designed a DC motor- based regenerative suspension, which consisted of a DC motor stator structure and an armature winding. This scheme achieved two working modes: energy harvesting and active controlling by combining the performances of both energy conservation and suspension maneuverability. Hydraulic regenerative shock absorbers can harvest the vibration energy and convert this energy into electricity by employing oscillatory motion to drive the power generator.

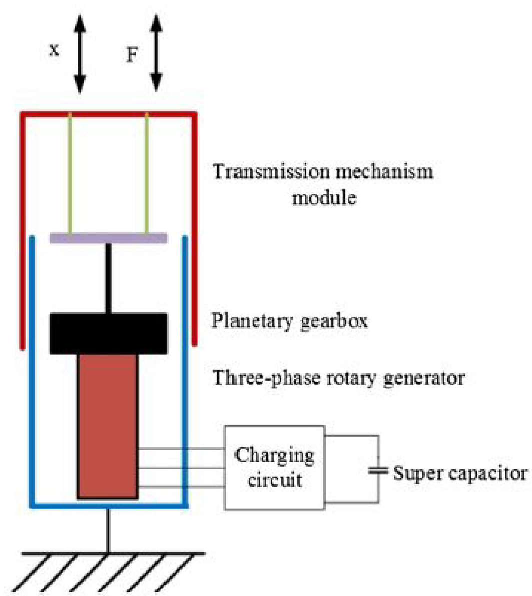
Many researchers have studied kinetic energy converting methods. They utilized commercial DC/AC motors as generators and focused on various methods to drive these generators. A number of studies reformed the existing hydraulic shock absorber and utilized the oil in the shock absorber to flow into a side oil circuit. They normally use the flowing fluid to drive a hydraulic motor, which is connected in parallel to a DC/AC generator. Check valves are also used to ensure unidirectional fluid flow and unidirectional rotation of the hydraulic motor. In, the authors presented a hydraulic rectifier to integrate the shock absorber and the energy harvesting. A maximum energy harvesting efficiency of 38.81% was achieved in the proposed regenerative shock absorber with an amplitude of 8 mm and a frequency of 2 Hz. The third category is mechanical design, which is developed rapidly because of a greater efficiency and average power. In previous studies, ball screws have been used for the transmission of regenerative shock absorbers for the sake of good stiffness and transmitting efficiency. Sabzehgar and Maravandi designed and improved an energy regenerative suspension using an algebraic screw linkage in. A hexagon linkage was used in the initial design, and a two-leg linkage was presented in latter schemes. The algebraic linkage achieved a relatively high mechanical efficiency between 0.71 and 0.84, which is highly constructive for the overall efficiency. Gupta et al. compared different electromagnetic shock absorbers and found that rotary schemes had large power compared with the linear schemes in bench tests. The results also indicated that rack and gears have the potential to drive a larger DC/AC motor to achieve greater power density. In , Zooidal. analyzed and modeled an equivalent circuit for an electromagnetic regenerative shock absorber using a rack and gears. This model assisted the evaluation and optimization of the rack-and-gears schemes. Rack-and-gears regenerative shock absorbers based on a mechanical design were rapidly developed because of their high efficiency and average power. Zhang et al. patented an energy regenerative shock absorber based on a rack-and-gears transmission and a DC motor in. Li et al. proposed an energy harvesting shock absorber by assembling a rack-and-gears transmission and a DC motor. Their bench and road tests revealed a peak power of 67.5W and an average power of 19.2W at 48 km/h. In the sequent work, the authors in presented a retrofitted rack-and-gears transmission . With a pair of one-way clutches, this new transmission converted the reciprocating motion of the shock absorber into the successive and unidirectional rotation of a DC motor. This improvement resulted in an efficiency of greater than 60%. Although the existing approaches have partly covered the energy harvesting problems in shock absorbers, some facets of regenerative shock absorbers still remain unclear. There are at least two aspects that need to be improved: (1) The applications of regenerative shock absorber are rarely studied and the storage system of generated power has not been designed. (2) The efficiency and structural simplicity are in conflict when considering both high efficiency and a reliably simple structure. To tackle these aspects of existing designs, in this project, we proposed a high-efficiency energy regenerative shock absorber using a rack and gears transmission with the storage of a super capacitor, which was used to extend the battery endurance and cruising range of an EV. The use of regenerative shock absorbers in EVs is clearly structured and described in this project in the field, including the utilization of a super capacitor. Additionally, the mechanical design of the shock absorbers also achieves high efficiency and reliability, which transmits the random and bi-directional vibration into stable and uni-directional rotation for effective power generation. The rest of this project is organized as follows. [4]

System design

The general architecture of our energy regenerative shock absorber using super capacitors, which is applied to extend the battery endurance of EVs, has four main parts:

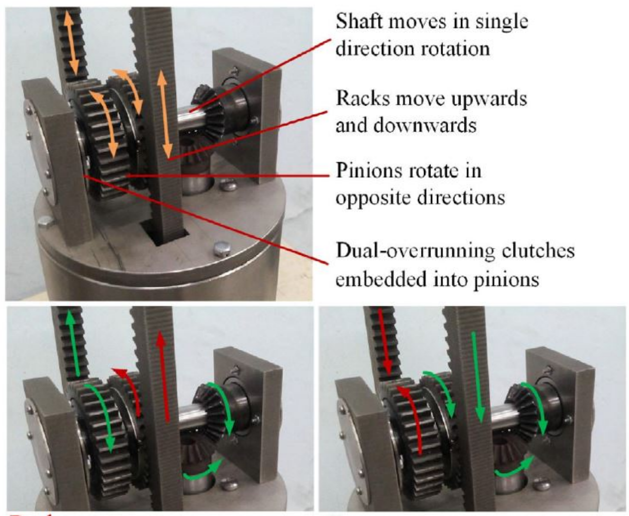
(1) Suspension vibration input module,
(2) Transmission module,
(3) Generator module and
(4) Power storage module.

Acting as the energy input, when an EV is driving on a road, the road roughness will induce suspension vibration and there will be a linear motion between the two cylinders of the regenerative shock absorber. Therefore, the two cylinders of the energy regenerative shock absorber are defined as the suspension vibration input module. The function of the transmission mechanism module is to convert the bidirectional vibration between the two cylinders to unidirectional rotation for the input shaft of the generator, which greatly improve reliability and increase efficiency. The generator module will be driven in one direction to generate electricity and to convert the kinetic energy into electrical energy. The purpose of the power storage module connected to the generator module is to store the regenerative energy of the shock absorber in the super capacitor, which is applied to an EV to improve the cruising mileage. [10]

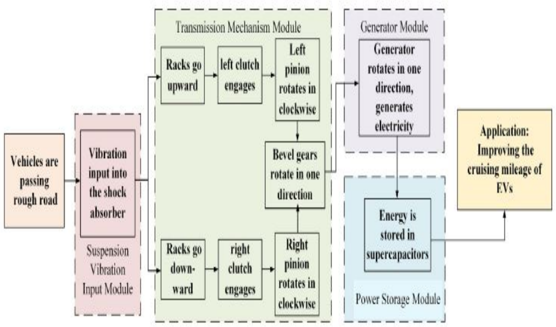


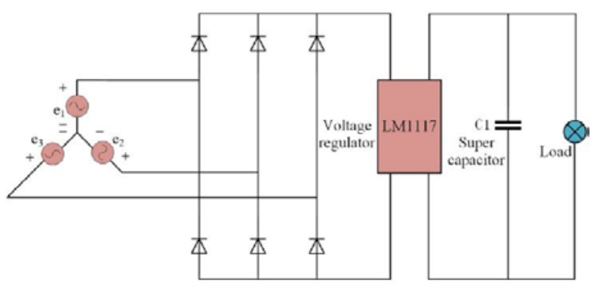
THE WORKING PRINCIPLE

The working principle of the bi-directional conversion to a unidirectional conversion mechanism. Red arrows indicate the pinion disengaged from the shaft. And green arrows indicate the engaged pinion and other transmission, which show the transmitting route of motion from vertical to rotational. Two bevel gears are used to transfer the rotational motion of the shaft by 90_. In addition, the bevel gears can add a transmission ratio if necessary. In this manner, the transmission mechanism module of the energy regenerative shock absorber based on dual overrunning clutches can convert the linear oscillation of the suspension vibration to a unidirectional rotation for the input shaft of the generator.



The power storage module



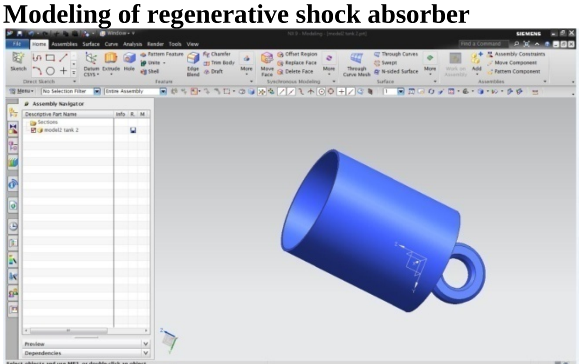


(a) Electric circuit for energy regenerative shock absorber

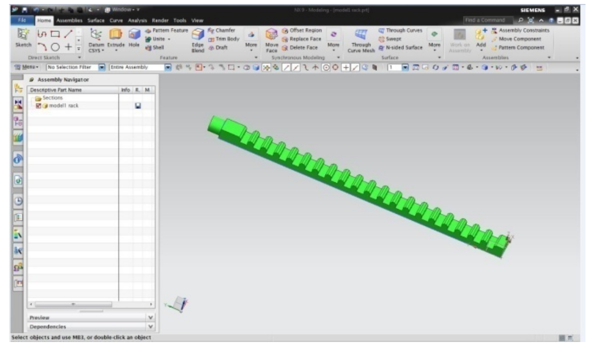
MODELING

The energy regenerative shock absorber has several parts, such as the generator, planetary gearbox, bevel gear, and rack pinion. The objective of this session is to investigate the influence of these components and the parameters on the dynamics of the system.

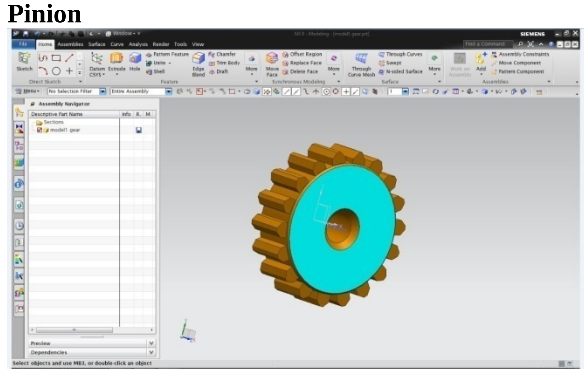
Modeling of regenerative shock absorber



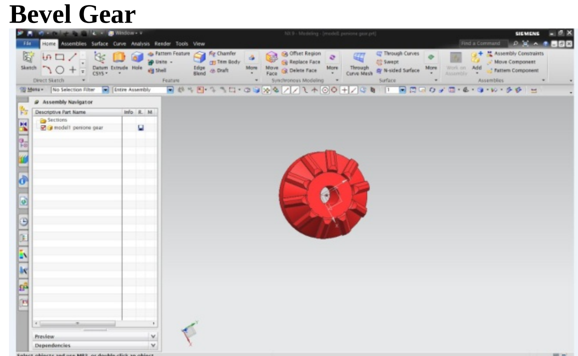
Rack



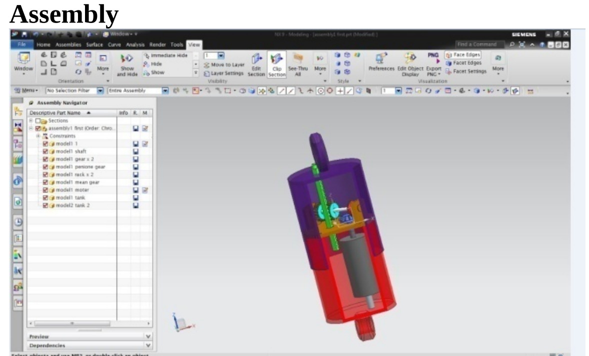
Pinion



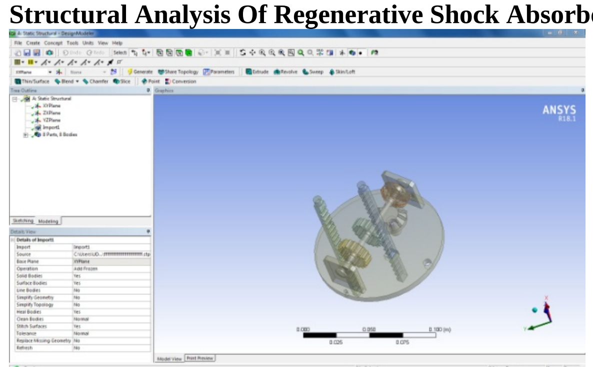
Bevel Gear

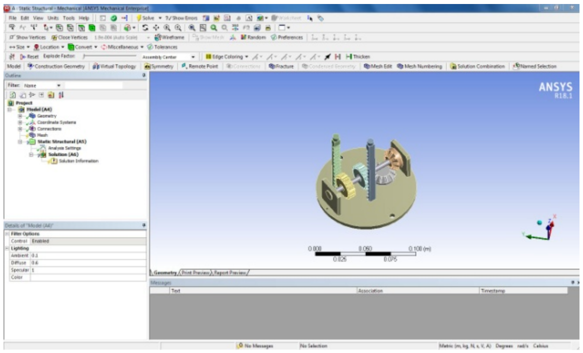


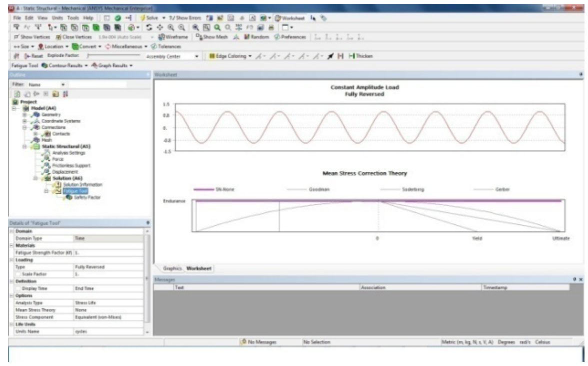
Assembly

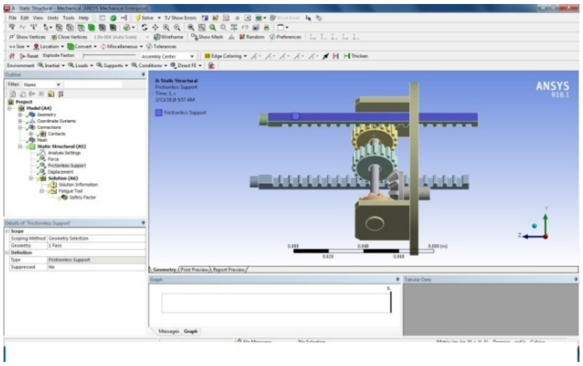


Structural Analysis Of Regenerative Shock Absorber



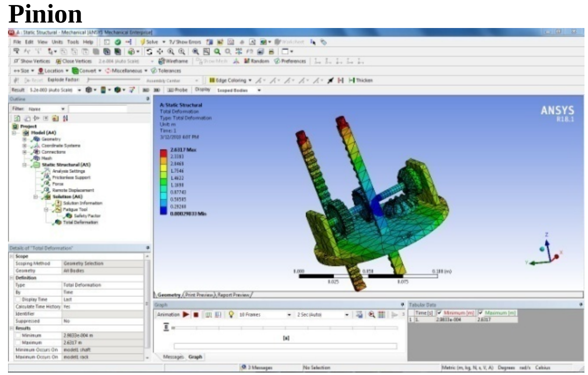






Applying Fatigue Tool Parameters

Detailed View Of Safety Factor Of Rack and Pinion



Result & Solutions

TABLE 1

Model (A4) > Geometry > Parts

Object Name	*model1 mean gear*	*model1 rack*	*model1 rack*	*model1 pinion gear*	*model1 gear*	*model1 gear*	*model1 shaft*	*model1 1*
State	Meshed							
Graphics Properties								
Visible	Yes							
Transparency	1							
Definition								
Suppressed	No							
Stiffness Behavior	Flexible							
Coordinate System	Default Coordinate System							
Reference Temperature	By Environment							
Behavior	None							
Material								
Assignment	Mild Steel							
Nonlinear Effects	Yes							
Thermal Strain Effects	Yes							
Bounding Box								
Length X	2.7985e-002 m	8.4889e-003 m		1.9603e-002 m	2.3391e-002 m		6.0242e-002 m	0.1 m
Length Y	2.7985e-002 m	8.4816e-003 m		1.9776e-002 m	2.3462e-002 m		5.9966e-002 m	0.1 m
Length Z	2.3882e-002 m	0.125 m		2.2708e-002 m	2.5925e-002 m		5.e-003 m	3.6272e-002 m
Properties								
Volume	4.1237e-006	3.2649e-006 m³		3.0319e-006	3.4116e-006 m³		1.5708e-006	4.5283e-005

	m^3			m^3			m^3	m^3
Mass	3.2371e-002 kg	2.563e-002 kg		2.38e-002 kg	2.6781e-002 kg		1.2331e-002 kg	0.35547 kg
Centroid X	1.4196e-002 m	-1.2851e-002 m	-8.1397e-003 m	2.3548e-002 m	-2.8731e-003 m	-1.7761e-002 m	3.5447e-004 m	7.2315e-005 m
Centroid Y	-1.4069e-002 m	-7.9596e-003 m	2.8334e-002 m	-2.3392e-002 m	2.7835e-003 m	1.7594e-002 m	-3.5263e-004 m	-7.1939e-005 m
Centroid Z	1.0082e-002 m	3.5192e-002 m	2.9847e-002 m	2.4962e-002 m	2.5082e-002 m		2.5e-002 m	5.4202e-003 m
Moment of Inertia Ip1	1.7868e-006 kg·m^2	3.542e-005 kg·m^2		1.3577e-006 kg·m^2	2.0458e-006 kg·m^2		3.8144e-008 kg·m^2	2.0978e-004 kg·m^2
Moment of Inertia Ip2	1.7866e-006 kg·m^2	3.5477e-005 kg·m^2		8.4878e-007 kg·m^2	1.1604e-006 kg·m^2		6.5621e-006 kg·m^2	3.0846e-004 kg·m^2
Moment of Inertia Ip3	1.9034e-006 kg·m^2	1.4854e-007 kg·m^2		8.4831e-007 kg·m^2	1.1567e-006 kg·m^2		6.5621e-006 kg·m^2	4.7653e-004 kg·m^2
Statistics								
Nodes	5545	3121	3141	4935	9499	9573	2420	3220
Elements	3025	1433	1447	2792	5287	5344	451	1534
Mesh Metric	None							

TABLE 2
Model (A4) > Connections

Object Name	*Connections*
State	Fully Defined
Auto Detection	
Generate Automatic Connection On Refresh	Yes
Transparency	
Enabled	Yes

TABLE 3
Model (A4) > Connections > Contacts

Object Name	*Contacts*
State	Fully Defined
Definition	
Connection Type	Contact
Scope	
Scoping Method	Geometry Selection
Geometry	All Bodies
Auto Detection	
Tolerance Type	Slider
Tolerance Slider	0.
Tolerance Value	4.8082e-004 m
Use Range	No
Face/Face	Yes
Face Overlap Tolerance	Off
Cylindrical Faces	Include
Face/Edge	No
Edge/Edge	No
Priority	Include All
Group By	Bodies
Search Across	Bodies
Statistics	
Connections	9
Active Connections	9

Mesh **TABLE 4 Model (A4) > Mesh**

Object Name	*Mesh*
State	Solved
Display	
Display Style	Body Color
Defaults	
Physics Preference	Mechanical
Relevance	0
Element Order	Program Controlled
Sizing	
Size Function	Adaptive
Relevance Center	Coarse
Element Size	Default
Initial Size Seed	Assembly
Transition	Fast
Span Angle Center	Coarse
Automatic Mesh Based Defeaturing	On
Defeature Size	Default
Minimum Edge Length	1.2842e-006 m
Quality	
Check Mesh Quality	Yes, Errors
Error Limits	Standard Mechanical
Target Quality	Default (0.050000)
Smoothing	Medium
Mesh Metric	None
Inflation	
Use Automatic Inflation	None
Inflation Option	Smooth Transition
Transition Ratio	0.272
Maximum Layers	5
Growth Rate	1.2
Inflation Algorithm	Pre
View Advanced Options	No
Advanced	
Number of CPUs for Parallel Part Meshing	Program Controlled
Straight Sided Elements	No
Number of Retries	Default (4)
Rigid Body Behavior	Dimensionally Reduced
Mesh Morphing	Disabled
Triangle Surface Mesher	Program Controlled
Topology Checking	No
Pinch Tolerance	Please Define
Generate Pinch on Refresh	No
Statistics	
Nodes	41454
Elements	21313

TABLE 5
Model (A4) > Static Structural (A5) > Loads

Object Name	*Frictionless Support*	*Force*	*Remote Displacement*
State	Fully Defined		
Scope			

Scoping Method	Geometry Selection		
Geometry	1 Face		
Coordinate System			Global Coordinate System
X Coordinate			3.5447e-004 m
Y Coordinate			-3.5263e-004 m
Z Coordinate			2.5e-002 m
Location			Defined
Definition			
Type	Frictionless Support	Force	Remote Displacement
Suppressed	No		
Define By		Components	
Coordinate System		Global Coordinate System	
X Component		0. N (ramped)	0. m (ramped)
Y Component		0. N (ramped)	0. m (ramped)
Z Component		-2000. N (ramped)	0. m (ramped)
Rotation X			Free
Rotation Y			Free
Rotation Z			Free
Behavior			Deformable
Advanced			
Pinball Region			All

Solution (A6)

Model (A4) > Static Structural (A5) > Solution (A6) > Fatigue Tools

Object Name	*Fatigue Tool*
State	Solved
Domain	
Domain Type	Time
Materials	
Fatigue Strength Factor (Kf)	1.
Loading	
Type	Fully Reversed
Scale Factor	1.
Definition	
Display Time	End Time
Options	
Analysis Type	Stress Life
Mean Stress Theory	None
Stress Component	Equivalent (von-Mises)
Life Units	
Units Name	cycles
1 cycle is equal to	1. cycles

FIGURE 1

Model (A4) > Static Structural (A5) > Solution (A6) > Fatigue Tool

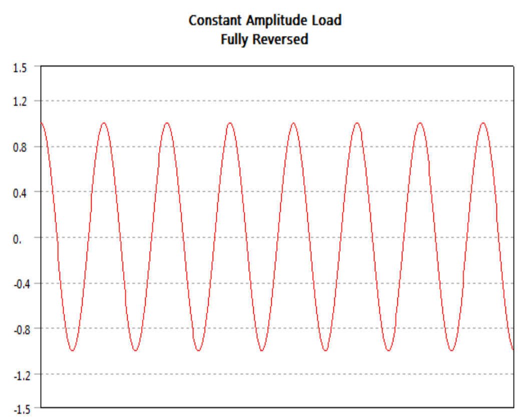


FIGURE 2

Model (A4) > Static Structurall (A5) > Solution (A6) > Fatigue Tool

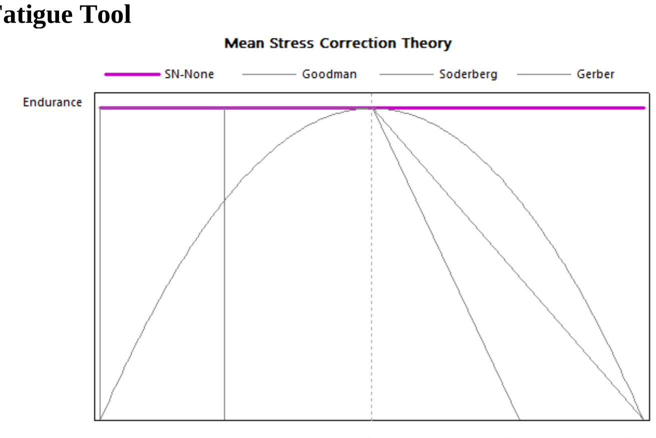


TABLE 6

Model (A4) > Static Structural (A5) > Solution (A6) > Fatigue Tool > Results

Object Name	*Safety Factor*
State	Solved
Scope	
Scoping Method	Geometry Selection
Geometry	All Bodies
Definition	
Design Life	1.e+009 cycles
Type	Safety Factor
Identifier	
Suppressed	No
Integration Point Results	
Average Across Bodies	No
Results	
Minimum	6.3713e-004
Minimum Occurs On	model1 shaft

TABLE 7
Model (A4) > Static Structural (A5) > Solution (A6) > Fatigue Tool > Safety Factor

Time [s]	Minimum	Maximum
1.	6.3713e-004	15.

TABLE 8
Model (A4) > Static Structural (A5) > Solution (A6) > Results

Object Name	*Total Deformation*
State	Solved
Scope	
Scoping Method	Geometry Selection
Geometry	All Bodies
Definition	
Type	Total Deformation
By	Time
Display Time	Last
Calculate Time History	Yes
Identifier	
Suppressed	No
Results	
Minimum	2.9833e-004 m
Maximum	2.6317 m
Minimum Occurs On	model1 shaft
Maximum Occurs On	model1 rack
Information	
Time	1. s
Load Step	1
Substep	1
Iteration Number	1

TABLE 9
Model (A4) > Static Structural (A5) > Solution (A6) > Total Deformation

Time [s]	Minimum [m]	Maximum [m]
1.	2.9833e-004	2.6317

Materials Data
Mild Steel

TABLE 10
Mild Steel > Constants

Density	7850 kg m^-3
Isotropic Secant Coefficient of Thermal Expansion	1.2e-005 C^-1
Specific Heat	434 J kg^-1 C^-1
Isotropic Thermal Conductivity	60.5 W m^-1 C^-1
Isotropic Resistivity	1.7e-007 ohm m

TABLE 11
Mild Steel > Compressive Yield Strength

Compressive Yield Strength Pa
2.5e+008

TABLE 12
Mild Steel > Tensile Yield Strength

Tensile Yield Strength Pa
2.5e+008

TABLE 13
Mild Steel > Tensile Ultimate Strength

Tensile Ultimate Strength Pa
4.6e+008

TABLE 14
Mild Steel > Isotropic Secant Coefficient of Thermal Expansion

Zero-Thermal-Strain Reference Temperature C
22

TABLE 15
Mild Steel > Strain-Life Parameters

Strength Coefficient Pa	Strength Exponent	Ductility Coefficient	Ductility Exponent	Cyclic Strength Coefficient Pa	Cyclic Strain Hardening Exponent
9.2e+008	-0.106	0.213	-0.47	1.e+009	0.2

TABLE 16
Mild Steel > Isotropic Elasticity

Temperature C	Young's Modulus Pa	Poisson's Ratio	Bulk Modulus Pa	Shear Modulus Pa
	2.e+011	0.3	1.6667e+011	7.6923e+010

CONCLUSION

An energy regenerative shock absorber is able to harvest the kinetic energy from the vehicle suspension vibration. This Project presented the design, modeling and analysis of a novel energy regenerative shock absorber based on dual-overrunning clutches for electrical vehicles. The shock absorber consists of four main components: the suspension vibration input module, the transmission module, the generator module and the power storage module. The suspension vibration input module is used to obtain a relative linear motion, and the function of the transmission mechanism module is to convert the up-and-down linear motion of the suspension vibration to a unidirectional rotation for the input shaft of the generator. The generator will be driven in one direction to generate electricity and convert the kinetic energy into electrical energy. The power storage module is used to store the power in the super capacitor and will be used by the EV to improve the cruising mileage. The results demonstrate that the energy regenerative shock absorber can provide damping for a typical passenger car. In addition, the energy regenerative shock absorber can provide variable damping coefficients by changing the external loads, i.e., this novel shock absorber can be applied to different types of vehicles. [13]

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