Performance of Active Control and Energy Harvesting of a Novel Suspension System

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Abstract. Several processes were employed to improve the defects lie in the existing energy-regenerative suspension, such as the low efficiency of energy harvesting, the lack of unified assessment standards on the performance of energy harvesting. Firstly, a novel suspension system was established with the energy harvesting could also be implemented while controlling, which would improve the efficiency of energy harvesting; Then power flow analysis method was adopted to realize the quantitative analysis on the performance of energy harvesting, 4 evaluation criteria on performance of energy harvesting were established in considering of relative energy-regenerative ability and absolute energy-regenerative ability, which would be used as the unified assessment standards. A LQR controller was presented to control and reduce the vibration of the novel suspension system. To optimize the weight coefficients of LQR active control algorithm, an improved genetic algorithm was designed with 5 improvements on both genetic operator and genetic mechanism. The simulations on the performance of active control of the novel suspension system were preformed, the results show that the riding comfort and handling stability of vehicle are both improved with the genetic-algorithm-optimized LQR controller. The simulations on the performance of energy harvesting of the novel suspension system under different road excitations were conducted, the results show that the assessment standards could represent the energy harvesting ability of suspension system, the novel suspension system provide a better energy harvesting efficiency, the self-powered of suspension system under standard road excitation is realized.

1. Introduction

The traditional passive suspension system can't meet the demands of ride comfort and handling stability in modern vehicle, moreover, modern vehicle is incapable of providing the extensive energy required by vibration control of active suspension system. An energy harvesting device was designed in the energy-regenerative active suspension to recover the energy that were dissipated as heat in traditional suspension system, reduce the energy consumption by active suspension system relatively. Attentions were paid to the energy-regenerative active suspension system recently for it can provide good drive performance with less energy consumption. The research on energy-regenerative suspension system was conducted since 1970s. In 1978, Karnopp [1-2] showed the causes of energy dissipation in suspension system, while the requirement of input energy was discussed. In 1999, Nakano [3-4] proved that the required energy for active control could be provided by the recovered energy of suspension system entirely. In 2005, Bose Corporation [5] developed an energy-regenerative suspension system in using of electro-magnetic actuator equipped with linear motor, the features of
vibration control and energy harvesting were tested and verified. The research of energy-regenerative suspension system in China was carried out mainly in several institutes and universities since 2000s. In 2005, Yu Fan [6-7], who worked in Shanghai Jiao Tong University, indicated that the required energy supplement for suspension system would decrease dramatically if the vibration energy recovered efficiently according to the comparison and analysis between the energy that damper dissipated and the energy that active control required. In 2009, Yu Changmiao [8-9], a researcher from Jilin University, noted that the dissipation power of damper is about 42.3% of the output power of engine, the harvesting of the dissipation power is of great significance and application value. In 2013, Zhang Jiye [10], who studied in Southwest Jiaotong University, designed an energy-regenerative suspension system based on linear-motor-type electro-magnetic actuator, the conditions of the suspension system energy balance were presented. A novel energy-regenerative active suspension (NEAS) was proposed, the coexistence of active control and energy harvesting in the entire process was realized. An LQR active control algorithm was provided and accompanied with an improved genetic algorithm in optimizing its weight coefficients. The flowing and transforming processes of power of suspension system under passive energy-harvesting mode and active-control mode were put forward based on power flow method, the corresponding quantitative analysis method, evaluation criteria and calculation formula of performance of energy harvesting were presented to provide a uniform standard for theoretical analysis.

2. Model of NEAS
The damper of passive suspension system was substituted by an electro-magnetic actuator to develop the current energy-regenerative active suspension system, the actuator of the system could produce required control force according to the relevant control signal to get better vibration control effectiveness and recover the vibration energy in suspension system. The electro-magnetic actuator is the key component of current suspension system to realize vibration control and energy harvesting, which was used as both active control device and energy harvesting device, the alternation between the two operating modes were determined by the active control algorithm. A compromise should be made between the vibration control effectiveness and energy harvesting efficiency, which leads to that the recovered energy are not as much as what was designed. Moreover, much additional energy should be provided to implement active control. A NEAS was designed with the active control device and energy harvesting device work separately, as shown in figure 1, a motor was used as actuator to implement active control, a generator was used as energy-regenerator to implement energy harvesting, a movement mode convertor, that was equipped with the gear rack mechanism, was employed to combine the actuator and the energy-regenerator as electro-magnetic actuator of NEAS, which made it possible that active control and energy harvesting could be implemented simultaneously and with high efficiency.

![Figure 1. Electro-magnetic actuator of NEAS.](image)

The 2-DOF (two-degree-of-freedom) quarter-car model was taken as the subject of the study for it could reveal major kinematics features of suspension system. The basic assumptions of the 2-DOF
quarter-car model [11] are: (1) it is strictly symmetric on the left side and the right side of the vehicle; (2) the influence between the front side and the rear side of the vehicle are insignificant; (3) the vertical kinematics features of tyre could be simplified as spring. The 2-DOF quarter-car model of NEAS is shown in figure 2. The associated parameters include: the sprung mass \( m_s \), the unsprung mass \( m_t \), the suspension spring constant \( k_s \), the tyre spring constant \( k_t \), the mechanical damping of actuator \( c_{mmn} \), the electro-magnetic force of actuator \( F_{an} \), the mechanical damping of energy-regenerator \( c_{mgn} \), the electro-magnetic damping of energy-regenerator \( c_{egn} \). Let \( x_s \), \( x_t \), and \( x_r \) be the vertical displacements of the sprung mass, the unsprung mass and the road excitation respectively.

![Figure 2. 2-DOF quarter-car model of NEAS.](image)

The kinematic differential equations of NEAS can be described as in

\[
\begin{align*}
    m_s \ddot{x}_s + c_{mmn} (\dot{x}_s - \dot{x}_r) + c_{mgn} (\dot{x}_s - \dot{x}_r) + c_{egn} (\dot{x}_s - \dot{x}_r) + k_t (x_s - x_t) + F_{an} &= 0 \\
    m_t \ddot{x}_t - c_{mmn} (\dot{x}_r - \dot{x}_t) - c_{mgn} (\dot{x}_r - \dot{x}_t) - c_{egn} (\dot{x}_r - \dot{x}_t) - k_s (x_s - x_t) + k_t (x_s - x_t) - F_{an} &= 0
\end{align*}
\]

3. Active Control Algorithm

3.1. LQR active control algorithm

Take \( X = [x_s \ x_t \ \dot{x}_s \ \dot{x}_t] \) as state vector, then the differential equations of NEAS can be expressed in the form of the following state equation

\[
\dot{X} = AX + BU
\]

where, the variables \( A, B, U \) are shown as follow

\[
A = \begin{bmatrix}
    0 & 0 & 1 & 0 & 0 \\
    0 & 0 & 0 & 1 & 0 \\
    -k_s/m_s & k_t/m_t & -c_{mmn}/m_s & -c_{mgn}/m_s & c_{egn}/m_t \\
    k_t/m_t & -k_s/m_s & c_{mmn}/m_t & c_{mgn}/m_t & -c_{egn}/m_s \\
    0 & 0 & m_s & m_t & -2\pi f
\end{bmatrix},
B = \begin{bmatrix}
    0 \\
    0 \\
    -1/m_s \\
    1/m_t \\
    0
\end{bmatrix},
U = F_{an}
\]

where, \( f \) is instantaneous frequency of road excitation, the phase difference between displacement and velocity of road excitation was ignored.

Take \( Y = [\ddot{x}_s \ x_t - x_r \ x_s - x_t] \) as output vector, the output equation of the system can be described as

\[
Y = CX + DU
\]

where, the variables \( C, D \) are shown as follow
There are mainly 3 evaluation indexes about the performance of suspension system, the sprung mass acceleration, which represents ride comfort, the dynamic load of tyre, which indicates handling stability, the dynamic deflection of suspension, which means driving safety. The LQR active control algorithm was adopted in controlling of NEAS, the objective function of LQR \([6, 12]\) was derived from

\[
J = \lim_{T \to \infty} \frac{1}{T} \int_0^T \left[ q_1 \dot{x}_1^2 + q_2 (x_2 - x_1) + q_3 (x_3 - x_2) \right] dt
\]

where, \(q_1, q_2, q_3\) are the weighting coefficients of the acceleration of spring mass, the dynamic load of tyre, the dynamic deflection of suspension respectively.

Substituted equation (4) into equation (5), then the objective function becomes

\[
J = \lim_{T \to \infty} \frac{1}{T} \int_0^T \left[ Y^T Q Y \right] dt = \lim_{T \to \infty} \frac{1}{T} \int_0^T \left[ X^T Q X + U^T R U + 2X^T N U \right] dt
\]

where, \(Q = C^T Q, C, R = D^T Q, D, N = C^T Q, D\).

The control aim of suspension system of vehicle is that the concerned suspension states, such as sprung mass acceleration, dynamic load of tyre and dynamic deflection of suspension, are forced to return to their balance states (take it as zero state) under the LQR active control with acceptable quantity of energy consumption when they are drifting from or deviating from the zero states. The optimization control of suspension system is to calculate and utilize the optimal control force \(U\) to transfer the initial suspension state \(X_0\) to zero state in the limitless time period \([t_0, \infty)\) while minimizing the function value of the objective function of LQR active control algorithm as is defined in equation (6). Hence, the optimization control of suspension system could be presented as in

\[
U = \left\{ \min J | \dot{X} = AX + BU \right\}
\]

The equation (7) indicates a functional condition extremum problem, the optimal control force provided by the electro-magnetic actuator could be expressed as

\[
U = -KX = -R^{-1} (B^T P + N^T) X
\]

where, \(K\) is the optimal state feedback gain matrix, \(P\) could be worked out from the following Riccati equation

\[
PA + A^T P - (PB + N^T) R^{-1} (B^T P + N^T) + Q = 0
\]
operator [15]. For this reason, genetic algorithm was introduced and brought into the process of LQR controller designing to optimize the weight coefficients of LQR active control algorithm taking advantage of and using the parallel optimization and global optimization ability of genetic algorithm. There are 5 basic issues should be discussed when using genetic algorithm to optimize the weight coefficients of LQR controller [16]:

a. chromosome encoding
Chromosomes are encoded in integer, of which the length is determined by the number of the unknown parameters in $Q_0$, the unknown parameters are set in each gene on chromosome. Hence, the chromosome could be described as

$$Ch = (q_1, q_2, q_3)$$

(10)

b. chromosome population generating
A certain number chromosome are generated randomly according to the requirement of calculating to compose the initial chromosome population, which is

$$POP = (Ch_1, Ch_2, ..., Ch_N)$$

(11)

where, $N$ is the scale of the chromosome population.

c. fitness function constituting
The fitness function of genetic algorithm could be expressed by the 3 evaluation indexes on suspension system performance. However, some conformation measurements should be implemented to deal with the inconformity and discordancy of the unit and magnitude of the evaluation indexes. The passive suspension system with the identical working conditions was adopted as a comparison of the evaluation index to validate the fitness function constituted with the 3 evaluation indexes and make the fitness function effective and efficient [17-18]. Thus, the fitness function was constituted as

$$
\text{min } Fitness = \alpha \frac{\text{SMA}(Ch)}{\text{SMA}_p(Ch)} + \beta \frac{\text{DTD}(Ch)}{\text{DTD}_p(Ch)} + \gamma \frac{\text{DDS}(Ch)}{\text{DDS}_p(Ch)}
$$

(12)

where, SMA, DTD, and DDS are the root mean square value of sprung mass acceleration, dynamic tyre deformation, and dynamic deformation of suspension respectively, while SMA$_p$, DTD$_p$, and DDS$_p$ are all that of the passive suspension respectively; $\alpha$, $\beta$, and $\gamma$ are the weight coefficients of the fitness function. The dynamic tyre deformation is the relative position of unsprung mass and road excitation $x_t - x_r$, it’s a multiple of the dynamic load of tyre with a constant. The dynamic tyre deformation was used to evaluate the handling stability of suspension system of vehicle instead of the dynamic load of tyre in the entire paper, for which is much easier to be obtained by sensors and will simplify the calculations on fitness function.

d. genetic operator setting
There are 3 main genetic operators in standard genetic algorithm, which are selection operator, crossover operator and mutation operator. Chromosomes are chosen under selection operator using proportion selection method, generate the chromosomes of next generation under crossover operator using single-point crossover method, amend the chromosomes of next generation under mutation operator with single-point mutation method. The crossover probability and the mutation probability are constants throughout the iteration and evolution of genes on the chromosomes in the population. The population of chromosome keeps unchanged in executing certain number of genetic operators.

e. termination criterion designing
The number of iterations is employed as the termination criterion to determine the evolution is accomplished or not.

3.3. Improvements of genetic algorithm
The identification and optimization of the weight coefficients of LQR active control algorithm is an offline processing, which means the optimization of the weight coefficients of LQR controller and the
application of LQR algorithm in suspension system is relatively independent, the real-time character of genetic algorithm is inconsiderable and could be ignored. For this reason, some more complicated and efficient genetic strategies could be implemented to provide a more effective and powerful LQR algorithm. There are mainly 2 ways to improve genetic algorithm, in genetic operator and in genetic mechanism. 2 improvements were made on genetic operators, which are the selection operator with self-adaptation tournament method and multi-chromosome crossover operator; 3 improvements were made on genetic mechanisms, which are initial chromosome population optimization, elite chromosome reservation, optimal chromosomes suppression.

a. selection operator with self-adaptation tournament method
Selection operator is mainly focus on choosing the better chromosomes which would be passed on to the next generation of chromosome population directly or indirectly. The selection operator with self-adaptation tournament method is based on the comparison of the fitness of chromosomes, of which the principle is that a certain number of chromosomes are chosen randomly to compose as a group, the chromosomes in the group compete with each other till the one with best fitness is left, which eventually is to be the chosen one of this round [19].

b. multi-chromosome crossover operator
Crossover operator is used to generate new chromosomes for the next generation of chromosome population in exchanging some parts of genes randomly in a certain way with two chromosomes in current generation of chromosome population which have been processed with selection operator. The multi-chromosome crossover operator designed in this paper makes the best use of the genes in multiple chromosomes, which could enhance the activeness of chromosome and avoid the locality and one-sidedness of standard crossover operator. The crossover of the genes of chromosomes with multi-chromosome crossover operator is unidirectional, only the one which is set as the gene receiver alters its genes, the others which are working as the gene provider remain unchanged, the dominant chromosome for crossover in each execution as the gene provider and the gene for crossover at each time on the provider are determined by the shielding pattern [20-21].

c. initial chromosome population optimization
The initial chromosome population in standard genetic algorithm is generated randomly, of which the fitness is rather bad. As the iteration runs, the inferior genes on chromosome die out easily, quickly the chromosome population traps into local optimum. Yet chromosome with genes relatively better fitness could be generated as the standard genetic algorithm performs. Run the standard genetic algorithm repeatedly until the number of better chromosomes generated meets the require of chromosome population, then take this group of chromosomes as an initial chromosome population, which is with better genes and better fitness, could improve the optimal ability of genetic algorithm.

d. elite chromosome reservation
The chromosome with the best fitness in the current generation should be protected and reserved as an elite, it should be selected and reproduced to the next generation without alter and modify by crossover operator and mutation operator, which ensures that the best chromosome won’t be decomposed by genetic operators and also the convergence of fitness is monotonically increasing, consequently the running efficiency of genetic algorithm is improved.

e. optimal chromosomes suppression
As the iteration runs, the diversity of genes on chromosome in the population is weakened and lessened at the mid-latter stage. Many chromosomes which are identical with the best one emerge and be produced, which means the optimal ability of genetic algorithm at these stages is reduced and lowered. The optimal chromosomes suppression mechanism is to alter the genes on the chromosomes which are identical with the best one with high-frequency mutation at the mid-latter stage, which could increase the diversity of genes on chromosome and improve the running efficiency of genetic algorithm at these stages notably.
4. Quantitative Analysis of Performance of Energy Harvesting

The performance of energy harvesting of suspension system relate to the suspension structure itself, operating mode and road excitation. The flowing and transforming processes of power with the corresponding computational formula in the NEAS were provided based on power flow method. The uniform standard on quantify and analyze the performance of energy harvesting of suspension system were established.

4.1. Power flow analysis

There are two operating modes existing in NEAS, the passive energy-harvesting mode and the active-control mode, the flowing and transforming processes of power are different under each operating mode.

While in passive energy-harvesting mode, as shown in figure 3, the behaviors and functions of energy-regenerator and actuator in NEAS are the same, they are both used as passive dampers to recover vibration energy. The absorption power of suspension system is mainly obtained from the output power of engine, flows towards two directions, one is dissipated by passive damping of energy-regenerator and actuator, the other is absorbed by electro-magnetic damping of energy-regenerator and actuator. Then part of the second power is dissipated by the internal-resistance of energy-regenerator and actuator, the other part is taken as output power, approximately as regenerative power of suspension system. Thus, the absorption power of NEAS while in passive energy-harvesting mode can be expressed as

\[ P_{pri} = P_{pre} + P_{pdm} \]

where, \( P_{pre} \) is the total absorption power of electro-magnetic damping of suspension system, \( P_{pdm} \) is the total absorption power of passive damping of suspension system, which are given respectively as

\[ P_{pre} = P_{preg} + P_{prea} = (c_{prea} + c_{susp})(\dot{x}_1 - \dot{x}_2)^2 \]  
(14)

\[ P_{pdm} = P_{pddg} + P_{pdm} = (c_{pdmg} + c_{pdmm})(\dot{x}_1 - \dot{x}_2)^2 \]  
(15)

![Figure 3. The power flow of NEAS in passive energy-harvesting mode.](image)

The output power of NEAS while in passive energy-harvesting mode is shown as

\[ P_{pro} = P_{pre} - P_{pdi} \]

where, \( P_{pdi} \) is the total dissipation power of internal-resistance of suspension system, it could be described as

\[ P_{pdi} = P_{pdig} + P_{pdim} = I_{ig}^2 R_{gdg} + I_{im}^2 R_{dim} \]

(17)
While in active-control mode, the NEAS shows two operating states as the power flowing and transforming, which are achievable active control and attenuatable active control.

It is achievable active control when the active control force provided by the actuator is dominating the kinematic states of NEAS, which implies that the NEAS is capable of reaching the desired control state. As shown in figure 4(a), the absorption power of suspension system is mainly obtained from the output power of engine, after the dissipation of internal-resistance of actuator, it is absorbed by electro-magnetic damping of actuator to produce the control force, then the power flows towards three directions, one is dissipated by passive damping of energy-regenerator and actuator, another is absorbed by electro-magnetic damping of energy-regenerator, then part of the second power is dissipated by the internal-resistance of energy-regenerator, the other part is taken as output power of suspension system, the remained power is output by the electro-magnetic suspension system to change the kinematic states and control the vibration states.

It is attenuatable active control when the road excitation is dominating the kinematic states of NEAS, which indicates that the NEAS is incapable of reaching the desired control state, it could only reduce the deterioration tendency of vehicle vibration. As shown in figure 4(b), the power flow of attenuatable active control state is similar to passive energy-harvesting mode of NEAS, which doesn’t consume the power of source, but the absorption power of electro-magnetic damping of actuator is dissipated by internal-resistance and load-resistance, which can’t be recovered. Thus, the required power of NEAS while in active-control mode can be expressed as

\[
P_{an} = \begin{cases} P_e + P_{dmm} \cdot \left( \ddot{x} - \ddot{x} \right) & F_{an} \cdot \left( \ddot{x} - \ddot{x} \right) > 0 \\ 0 & F_{an} \cdot \left( \ddot{x} - \ddot{x} \right) \leq 0 \end{cases}
\]  

(18)

\[ P_{an} = F_{an} \left( \dot{x} - \dot{x} \right) \]  

(19)

\[ P_{dmm} = I_{an}^2 R_{dmm} \]  

(20)

The energy harvesting power of NEAS while in active-control mode is shown as

\[ P_{an} = P_{reg} - P_{dmg} \]  

(21)

\[ P_{reg} = c_{reg} \left( \dot{x} - \dot{x} \right)^2 \]  

(22)

\[ P_{dmg} = I_{an}^2 R_{dmg} \]  

(23)

\[ P_{co} \rightarrow \text{control - dominated} \]

\[ P_{ro} \rightarrow \text{output power of engine} \]

\[ P_{lo} \rightarrow \text{output power of source} \]

\[ P_{co} \rightarrow \text{output power of suspension} \]

\[ P_{ro} \rightarrow \text{absorption power of suspension} \]

\[ P_{ro} \rightarrow \text{absorption power of electro-magnetic damping of energy-regenerator} \]

\[ P_{dmg} \rightarrow \text{dissipation power of internal-resistance of actuator} \]

\[ P_{dmg} \rightarrow \text{dissipation power of internal-resistance of energy-regenerator} \]

\[ P_{reg} \rightarrow \text{dissipation power of passive damping of energy-regenerator} \]

\[ P_{reg} \rightarrow \text{output power of suspension} \]

\[ P_{reg} \rightarrow \text{regenerative power of suspension} \]

\[ P_{co} \rightarrow \text{to control the vehicle states} \]
4.2. Evaluation criteria of performance of energy harvesting

Four evaluation criteria were presented to provide uniform standard for the analysis and calculation on performance of energy harvesting of suspension system based on the operating mode and power flow analysis method.

(1) Potentiality of Energy Harvesting
Define the ratio of average output power $P_{\text{pro}}$ to average absorption power $P_{\text{pri}}$ while the suspension system is operating in passive energy-harvesting mode as the potentiality of energy harvesting (PER), which is shown as

$$\eta_p = \frac{P_{\text{pro}}}{P_{\text{pri}}} \times 100\%$$ (24)

(2) Effectiveness of Energy Harvesting
Define the ratio of average output power of energy harvesting $P_{\text{ro}}$ while the suspension system is operating in active-control mode to average output power $P_{\text{pro}}$ while the suspension system is operating in passive energy-harvesting mode as the effectiveness of energy harvesting (EER), which is shown as

$$\lambda_e = \frac{P_{\text{ro}}}{P_{\text{pro}}}$$ (25)

(3) Self-power Coefficient
Define the ratio of average output power of energy harvesting $P_{\text{ro}}$ to average required power of active control $P_{\text{cn}}$ while the suspension system is operating in active-control mode as the self-power coefficient, which is shown as

$$\gamma = \frac{P_{\text{ro}}}{P_{\text{cn}}}$$ (26)

(4) Average Output Power of Energy Harvesting
As relative evaluation criteria, the PER, EER, self-power coefficient could evaluate the relative performance of energy harvesting of suspension system, which couldn’t reflect the absolute performance of energy harvesting. For this reason, the average output power of energy harvesting $P_{\text{ro}}$
was taken as an absolute evaluation criterion to evaluate the absolute performance of energy harvesting of suspension system.

5. Simulation and Analysis of Performance of Active Control

The variation tendencies of best fitness and average fitness of the improved genetic algorithm in optimizing the weight coefficients of LQR active control algorithm are presented in figure 5. The figure illustrates that: 1) as the iteration runs, the best fitness of chromosome of improved genetic algorithm is monotonically decreasing, which means the improved genetic algorithm is valid and effective in optimizing the weight coefficients of LQR controller; 2) the best fitness of chromosome that the improved genetic algorithm generated is 2.575, the corresponding chromosome is (1,20000,100). Thus, the weight coefficients of LQR controller could be $q_1 = 1$, $q_2 = 20000$, $q_3 = 100$.

![Figure 5. Variation tendencies of fitness of improved genetic algorithm.](image)

5.1. Simulation in time domain

The running performance and the response characteristics of the suspension system with LQR active control algorithm which is optimized by improved genetic algorithm (LQR-IGA) are calculated and analyzed both in time domain and frequency domain with the comparisons of the corresponding passive suspension system (PASSIVE) and the suspension system with LQR active control algorithm of which the weight coefficients are based on the experiment of designer (LQR-EX). The weight coefficients of LQR-EX is given as $q_1 = 1$, $q_2 = 40000$, $q_3 = 500$.

The effects on vibration characteristics of suspension system of vehicle with LQR-IGA active control algorithm are analyzed. Considering the scenario that the vehicle is running on the level C road with the constant speed of 10 m/s last about 40 seconds. The comparisons on sprung mass acceleration, dynamic tyre deformation, dynamic deformation of suspension in time domain among PASSIVE, LQR-EX, LQR-IGA suspension system are shown in figure 6, figure 7 and figure 8, the corresponding states data of the response characteristics and their improvements are given in table 1. The figures and the data in Table 1 manifest that: 1) the sprung mass acceleration of suspension system with LQR-IGA control algorithm is much smaller than that of passive suspension system, that is a little smaller than the suspension system with LQR-EX control algorithm, which indicates that the riding comfort of the vehicle with LQR-IGA active control is the best of all, the riding comfort was improved by 52.66% compared with passive suspension system of vehicle; 2) the dynamic tyre deformation of suspension system with LQR-IGA control algorithm is a little smaller than that of passive suspension system, while that with LQR-EX control algorithm is a litter bigger than that of passive suspension system, which means that the handling stability of the vehicle with LQR-IGA active control is the best of all, the handling stability was improved only by 5.70% compared with passive suspension system of vehicle; 3) the dynamic deformation of suspension system with LQR-IGA control algorithm is larger than that of passive suspension system and that with LQR-EX control algorithm, but the dynamic deformation of suspensions in the 3 kinds of suspension system are all smaller than the permitted dynamic deformation (0.1 m), which indicates that the riding comfort and the handling stability of suspension system with LQR-IGA wouldn’t be worsened or deteriorated according to the dynamic deformation of suspension.
Table 1. Suspension state and its improvement

| Suspension state                  | PASSIVE State value | LQR-EX State value | Improvement | PASSIVE State value | LQR-IGA State value | Improvement |
|----------------------------------|---------------------|--------------------|-------------|---------------------|---------------------|-------------|
| Sprung mass acceleration         | 1.468               | 0.815              | 44.48%      | 0.696               | 52.66%              |
| Dynamic tyre deformation         | 0.00298             | 0.00317             | -6.38%      | 0.00281             | 5.70%               |
| Dynamic deformation of suspension| 0.00676             | 0.00702             | -3.85%      | 0.00783             | -15.78%             |

Figure 6. Comparison of sprung mass acceleration.

Figure 7. Comparison of dynamic tyre deformation.

Figure 8. Comparison of dynamic deformation of suspension.

5.2. Simulation in frequency domain
To make a further understanding about the effect of LQR-IGA active control algorithm on suspension system of vehicle, the comparisons of the PSD (power spectrum density) of sprung mass acceleration, dynamic tyre deformation, dynamic deformation of suspension in frequency domain are discussed and analyzed. With the adoption of the scenario of vehicle in the former section, the PSD of sprung mass acceleration, dynamic tyre deformation, dynamic deformation of suspension on LQR-IGA with the comparisons of PASSIVE and LQR-EX are revealed in figure 9 figure 10 and figure 11. The figures illustrate that: 1) in all but high resonance frequency range, the PSD of sprung mass acceleration of
LQR-EX and LQR-IGA are smaller than that of PASSIVE, the PSD of sprung mass acceleration of LQR-IGA is smaller than that of LQR-EX in low frequency range, low resonance frequency range and mid-frequency range; 2) the riding comfort of both the suspension systems of vehicle with LQR-EX and LQR-IGA is better than that with PASSIVE, the riding comfort of suspension system with LQR-IGA is a little better than that with LQR-EX; 3) the PSD of dynamic tyre deformation of LQR-EX and LQR-IGA are smaller than that of PASSIVE in low frequency range and low resonance frequency range, while that are bigger than PASSIVE in high resonance frequency range, PSD of dynamic tyre deformation of LQR-IGA is bigger than that of LQR-EX in low resonance frequency range and that is smaller than LQR-EX in high resonance frequency range; 4) the PSD of dynamic deformation of suspension system with LQR-EX and LQR-IGA are both improved in low resonance frequency range and deteriorated in low frequency range and high resonance frequency range compared with PASSIVE; the PSD of dynamic deformation of suspension system with LQR-IGA is bigger than that of LQR-EX in low frequency range, low resonance frequency range and high resonance frequency range.

![Figure 9. Comparison of the PSD of sprung mass acceleration.](image1)

![Figure 10. Comparison of the PSD of dynamic tyre deformation.](image2)
6. Simulation and Analysis of Performance of Energy Harvesting

Two types of energy-regenerative suspension system, which are novel energy-regenerative passive suspension (passive energy-harvesting mode of NEAS) and novel energy-regenerative active suspension (active-control mode of NEAS), were presented to analysis the performance of energy harvesting.

6.1. Performance of energy harvesting with standard road excitation

The bar charts of PER, EER, self-power coefficient and average output power of energy harvesting of NEAS on D level standard road with different vehicle speed are shown in figure 12. The PER of NEAS remains constant with the varying of vehicle speed is revealed in figure 12(a), which indicates that the PER is only associated with the suspension system itself; figure 12(b) illustrates that the EER decrease gradually as the vehicle speed rising; the EER is greater than 1 as the recovered energy of suspension system in active-control mode is more than that in passive energy-harvesting mode, it is because the vibration of sprung mass is reduced while the active control algorithm working, then the relative movement between sprung mass and unsprung mass is getting more fierce, thus more energy are recovered as the suspension system operating in active-control mode; figure 12(c) suggests that the self-power coefficient increase gradually as the vehicle speed rising; the self-power coefficient is greater than 1 as the recovered energy of suspension system in active-control mode is more than the required energy of active control, the entire self-sustaining of power supply is realized; figure 12(d) shows that the average output power of energy harvesting increase gradually as the vehicle speed rising.

Figure 12. The performance of energy harvesting of NEAS on D level standard road with different speed.
6.2. Performance of energy harvesting with sine road excitation
The variation tendency of PER of NEAS under sine road excitation with frequency from 0.5Hz to 15Hz and amplitude from 0.005m to 0.05m is shown in figure 13. The PER is invariable as the alternation of the frequency and amplitude of road excitation, which indicates that the PER of NEAS is only associated with the suspension system itself, independent of road excitation. The effects of parameters of suspension system on PER are discussed in reference [22-23].

![Figure 13. The PER of NEAS under sine road excitation.](image)

The variation tendency of EER of NEAS under sine road excitation with different frequency and amplitude is shown in figure 14, a reference plane, on which the EER is 1, is also presented in the drawing. It manifests that the satisfactory control effectiveness could be obtained with the LQR control algorithm in low frequency range, where high EER could be derived correspondingly; the case that the EER is lower than 1 occurred in medium frequency range for the reason that the variation of relative speed between sprung mass and unsprung mass of NEAS in active-control mode is similar with that in passive energy-harvesting mode, while only the energy-regenerator could recover energy in active-control mode, hence the EER is getting lower.

![Figure 14. The EER of NEAS under sine road excitation.](image)

The variation tendency of self-power coefficient of NEAS under sine road excitation with different frequency and amplitude is shown in figure 15, a reference plane, on which the self-power coefficient is 1, is also presented in figure 15. It illustrates that the self-power coefficient is independent of the frequency and amplitude of road excitation in low frequency range, which comes out to be smaller than 1, the system needs the supplement of external power; the self-power coefficient increases as the amplitude rises in the medium and high frequency range, the tendency of the increasing becomes more obvious as the frequency gets higher, moreover, the entire self-sustaining of power supply is realized; the self-power coefficient increases as the frequency rises, reaches to its maxima in the higher resonance frequency range, then getting lower, the tendency of rise then fall of self-power coefficient with frequency is more obvious as the amplitude gets higher; the entire self-sustaining of power supply could be realized as the frequency of road excitation higher than 1.72Hz when compared to the
reference plane; the self-power coefficient becomes smaller than 1 in a small range before it rising notably.

![Figure 15. The self-power coefficient of NEAS under sine road excitation.](image)

The variation tendency of average output power of energy harvesting of NEAS under sine road excitation with different frequency and amplitude is shown in figure 16. Conclusions could be made on this figure that the average output power of energy harvesting increase as the amplitude rise, the tendency of the increasing becomes more obvious as the frequency gets higher; the average output power of energy harvesting increases as the frequency rises, reaches to its maxima in the higher resonance frequency range, then getting lower, the tendency of rise then fall of average output power of energy harvesting with frequency is more obvious as the amplitude gets higher. The effects of other parameters of suspension system on the average output power of energy harvesting are discussed in reference [24].

![Figure 16. The average output power of energy harvesting of NEAS under sine road excitation.](image)

7. Conclusions
A NEAS system was designed with an electro-magnetic actuator, which includes actuator and energy-regenerator, to realize the simultaneous implementation of energy harvesting and active control. A LQR controller with an improved genetic algorithm in optimizing the weight coefficients of LQR active control algorithm was designed to attenuate and reduce the vibration of suspension system of vehicle. The flowing and transforming processes of power with the corresponding computational formula were provided based on the power flow method. Four evaluation criteria of performance of
energy harvesting of suspension system were presented to establish the uniform standard on quantify and analyse the performance of energy harvesting of suspension system.

The running performance of suspension system of vehicle with genetic-algorithm-optimized LQR controller are improved notably, of which the riding comfort is improved by 52.66% and the handling stability is improved by 5.70% in comparison of the passive suspension system. The frequency analysis shows that the improvement on riding comfort is effective in all but high resonance frequency range, the improvement on handling stability is valid in low frequency range and low resonance frequency range.

The PER only depends on the suspension system itself, it's exactly determined by the performance of energy harvesting device in suspension system; The EER, the self-power coefficient, the average output power of energy harvesting are related to the suspension system and the active control algorithm worked on it. High-efficiency active control algorithm, therefore, should be designed to improve the three evaluation criteria effectively. The simulation shows the variation tendencies of the evaluation criteria, but some basic data, such as the average output power of energy harvesting in the higher resonance frequency range, get too high with the ignorance of the limits of the ride comfort and the dynamic deflection of the suspension. The analyses of the areas, that the EER is lower than 1 and the self-power coefficient is smaller than 1, are insufficient. All the three problems will be studied in the future research.

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