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无外界动力源主动悬架的能量可用性

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摘 要:将无外界动力源的主动悬架在半主动模式下吸收平均功率与在主动模式下消耗平均功率的绝对值比作为能量可用性的评价指标,分析了优化 PID 与 LQG 控制主动悬架的性能与能量可用性。针对某重型汽车的 1/4 车主动悬架模型,设计了 PID 与 LQG 控制器。当悬架阻尼比为 0.1 时,以悬架二次型性能指标为目标函数,利用遗传算法对 PID 控制器参数进行了优化。发现优化 PID 控制主动悬架的二次型性能指标较 LQG 控制主动悬架大 3.32%,优化 PID 与 LQG 控制主动悬架的能量可用性评价指标分别为 17.15 和 226.33。分析结果表明:LQG 控制主动悬架的性能略优于优化 PID 控制主动悬架;2 种主动悬架均满足能量可用性要求,且 LQG 控制主动悬架的能量可用性远优于优化 PID 控制主动悬架。

关键词:汽车工程;主动悬架;无外界动力源;能量可用性;比例-微分-积分控制;线性二次型控制
中图分类号:U463.33 **文献标志码**:A

Energy availability of active suspension without external energy supply

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Abstract: The absolute ratio of mean power reclaimed in the semi-active control mode divided by the value consumed in the active control mode was proposed as the evaluating index of energy availability for active suspension without external energy supply (ASWEES). The performance and energy availability of ASWEES were analyzed based on optimized PID and LQG controllers, which were designed for a quarter-heavy-vehicle ASWEES. When the damping ratio was 0.1, PID control parameters were optimized by using the genetic algorithm with suspension quadratic performance index taken as the objective function. It is pointed that the suspension quadratic performance index of ASWEES based on optimized PID control is 3.32% bigger than the index based on LQG control, and their energy availability indexes are 17.15 and 226.33 respectively. The result indicates that the performance of ASWEES based on LQG control is weakly better, two ASWEESs meet the demand of energy availability, and the energy availability of ASWEES based on LQG control is strongly better. 6 tabs, 8 figs, 20 refs.

Key words: automotive engineering; active suspension; no external energy supply; energy availability; PID control; LQG control

0 Introduction

The active and semi-active suspensions are used to improve vehicle ride comfort[1-8]. It is usually believed that the performance of active suspension is more excellent than that of semi-active

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suspension. It is well known that the manufacturing and using costs of active suspension are higher than that of semi-active one because external power source and active force actuators are needed by the active suspension [3-8]. The energy conservation suspension technology is one of automotive research focuses[9-12]. Yu, et al analyzed the energy saving potential of electromagnetic energy regenerative suspension[13-14], and pointed that the suspension could recover some vibration energy. In fact, the suspension is a kind of semi-active suspensions. Huang, et al studied an electrical energy-regenerative suspension, and designed its main-loop controller with two modes, consumptive full-active (CFA) mode and regenerative semi-active (RSA) mode[11,15]. The former mode addresses sprung mass vibration control, however, the latter mode emphasizes energy regeneration. In fact, the suspension with CFA mode is a full-active suspension, and the suspension with RSA mode is a semi-active suspension.

Based on the suspension reclaiming energy[12], a new active suspension without external energy supply (ASWEES) is given. The character of ASWEES is that the reclaiming energy under the semi-active control mode is used to actively reduce vibration under the active control mode. So ASWEES needs no external energy supply. The energy availability is one of key questions for ASWEES. It is a necessary condition for ASWEES being feasible that the reclaiming energy under the semi-active control mode meets the energy demand to actively reduce vibration under the active control mode. Bigger is the value of the reclaiming power under the semi-active control mode subtracted by the power need to actively reduce vibration under the active control mode, better is the energy availability of ASWEES.

To investigate the energy availability of ASWEES, LQG and optimized PID controllers are designed for ASWEES based on a quarter-heavy-vehicle suspension model[16-20]. Comparative analysis on the ride comfort and energy availability of ASWEES using the two controllers is carried out.

1 Working principle and model of ASWEES

1.1 Working principle and model

Fig. 1 shows the working principle of ASWEES. When the direction of control force is contrary to that of relative velocity of sprung mass to unsprung mass, ASWEES is working in the semi-active control mode, and the reclaiming energy/active cylinder turns the suspension vibration into the hydraulic energy of the accumulator. When the direction of control force is the same as that of relative velocity of sprung mass to unsprung mass, ASWEES is working in the active control mode, and the accumulator gives actively reducing vibration energy to the suspension by the reclaiming energy/active cylinder. During a pulse-width-modulation (PWM) cycle, the actively reducing force or the semi-active damping force can be gotten when solenoid valves receive the corresponding PWM control signals from the control unit. According to Newton Second Law, the differential equations for ASWEES are written as follows

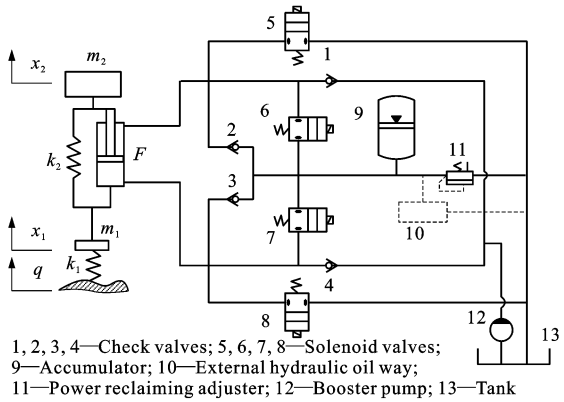

Fig. 1 Working principle of ASWEES

$$\begin{cases} m_1\ddot{x}_1 = -k_1(x_1-q)+k_2(x_2-x_1)+c_0(\dot{x}_2-\dot{x}_1)-F \\ m_2\ddot{x}_2 = -k_2(x_2-x_1)-c_0(\dot{x}_2-\dot{x}_1)+F \end{cases} \tag{1}$$

$$\dot{q} = 2\pi n_0 w\sqrt{G_q(n_0)u}-2\pi f_0 q \tag{2}$$

Where m_1 is unsprung mass; m_2 is sprung mass; k_1 is tire stiffness; k_2 is suspension stiffness; F is control force in general; c_0 is basal damping; q is the displacement input of suspension; n_0 is reference spatial frequency and equals 0.1 m^{-1}; w is road white-noise signal; $G_q(n_0)$ is road

roughness coefficient and is determined by road class; u is vehicle velocity; f_0 is lower cut off frequency and equals $0.011u$; x_1 is the vertical displacement of unsprung mass; x_2 is the vertical displacement of sprung mass.

Suspension system's state vector is

$$\boldsymbol{X}=(q,x_1,x_2,x_3,x_4)^{\mathrm{T}}$$

$$x_3=\dot{x}_1,\ x_4=\dot{x}_2$$

Its state-space model is

$$\dot{\boldsymbol{X}}=\boldsymbol{AX}+\boldsymbol{BU}+\boldsymbol{GW} \tag{3}$$

$$\boldsymbol{A}=\begin{bmatrix} -2\pi f_0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 \\ \dfrac{k_1}{m_1} & -\dfrac{k_1+k_2}{m_1} & \dfrac{k_2}{m_1} & -\dfrac{c_0}{m_1} & \dfrac{c_0}{m_1} \\ 0 & \dfrac{k_2}{m_2} & -\dfrac{k_2}{m_2} & \dfrac{c_0}{m_2} & -\dfrac{c_0}{m_2} \end{bmatrix}$$

$$\boldsymbol{B}=\begin{bmatrix} 0 & 0 & 0 & -\dfrac{1}{m_1} & \dfrac{1}{m_2} \end{bmatrix}^{\mathrm{T}}$$

$$\boldsymbol{G}=\begin{bmatrix} 2\pi n_0\sqrt{G_q(n_0)u} & 0 & 0 & 0 & 0 \end{bmatrix}^{\mathrm{T}}$$

$$\boldsymbol{U}=[F],\ \boldsymbol{W}=[w]$$

1.2 Evaluating index of ride comfort and energy availability

Suspension quadratic performance index is adopted as follow

$$J=\frac{1}{T}\int_0^T(a_2^2+\delta'_1F_{\mathrm{d}}^2+\delta_2f_{\mathrm{d}}^2)\mathrm{d}t \tag{4}$$

Where a_2 is the acceleration of sprung mass and equals $\ddot{x}_2$; F_{d} is the dynamic load of unspung mass and equals $k_1(x_1-q)$; f_{d} is suspension deflection and equals x_2-x_1; δ'_1 is the weight of F_{d}^2; δ_2 is the weight of f_{d}^2; T is the total running time of vehicle; t is time variable.

When F_{d} is taken by x_1-q, J is

$$J=\frac{1}{T}\int_0^T[\ddot{x}_2^2+\delta_1(x_1-q)^2+\delta_2(x_2-x_1)^2]\mathrm{d}t \tag{5}$$

Where δ_1 is the weight of $(x_1-q)^2$.

P is the power of reclaiming energy/active cylinder

$$P=F(\dot{x}_2-\dot{x}_1) \tag{6}$$

When $P>0$, the accumulator gives actively reducing vibration energy to the suspension by the reclaiming energy/active cylinder. When $P<0$, the reclaiming energy/active cylinder turns the suspension vibration into the hydraulic energy of the accumulator.

P_{s} is the mean power of the reclaiming energy/active cylinder in the semi-active control mode; P_{a} is the mean power in the active control mode

$$\begin{cases} P_{\mathrm{s}}=\dfrac{W_{\mathrm{s}}}{T}=\dfrac{1}{T}\displaystyle\int_0^T P\mathrm{d}t & P<0 \\ P_{\mathrm{a}}=\dfrac{W_{\mathrm{a}}}{T}=\dfrac{1}{T}\displaystyle\int_0^T P\mathrm{d}t & P>0 \end{cases} \tag{7}$$

Where W_{s} is the work of the reclaiming energy/active cylinder in the semi-active control mode; W_{a} is the work in the active control mode.

Obviously, P_{s} is positive and P_{a} is negative. When $\left|\dfrac{P_{\mathrm{s}}}{P_{\mathrm{a}}}\right|=1$, the reclaiming energy under the semi-active control mode justly meets the energy demand to actively reduce vibration under the active control mode in the ideal condition. Here, $\left|\dfrac{P_{\mathrm{s}}}{P_{\mathrm{a}}}\right|$ is proposed as the evaluating index for the energy availability of ASWEES. Bigger is $\left|\dfrac{P_{\mathrm{s}}}{P_{\mathrm{a}}}\right|$, Better is the energy availability of ASWEES.

1.3 Confirming δ_1 and δ_2

The ASWEES is reformed as a heavy vehicle passive suspension[12]. When u is 20 m·s^{-1} on an ISO C-class road, the parameters of passive suspension and road inputs are shown in Tab. 1. Here, c is the shock absorber damping of passive suspension.

Tab. 1 Parameters of passive suspension and road inputs

Parameter	Value	Parameter	Value
m_1/kg	350	k_1/(N·m^{-1})	3.0×10^6
m_2/kg	5 000	k_2/(N·m^{-1})	5.05×10^5
c/(N·s·m^{-1})	30 150	$G_q(n_0)$/(m^2·m^{-1})	2.56×10^{-4}
f_0/Hz	0.22		

According to Ref.[20], δ_1 and δ_2 are expressed as follows

$$\begin{cases} \delta_1=\beta_1\gamma_1 \\ \delta_2=\beta_2\gamma_2 \end{cases} \tag{8}$$

$$\sigma^2(a_2)=\beta_1\sigma^2(x_1-q)=\beta_2\sigma^2(f_{\mathrm{d}}) \tag{9}$$

$$W_1=\frac{W_2}{\gamma_1}=\frac{W_3}{\gamma_2} \tag{10}$$

$$W_1+W_2+W_3=1$$

Where β_1 and β_2 are the normalizing coefficients of

$(x_1-q)^2$ and f_d^2 relative to a_2^2 respectively; γ_1 and γ_2 are the subjective weights of $(x_1-q)^2$ and f_d^2 respectively when the weight of a_2^2 is 1; $\sigma^2(a_2)$, $\sigma^2(x_1-q)$ and $\sigma^2(f_d)$ are the variances of a_2, x_1-q and f_d respectively; W_1, W_2 and W_3 are the subjective weights of a_2, x_1-q and f_d respectively, and are gotten according to the relative importances of a_2, x_1-q and f_d.

Under the frequently-used condition of heavy vehicle, the importance of a_2 over f_d, the strong importance of a_2 over x_1-q, and the weak importance of x_1-q over f_d are demonstrated. The subjective weights are obtained in Tab. 2.

Tab. 2 Subjective weights

W_1	W_2	W_3	γ_1	γ_2
0.649 1	0.279 0	0.071 9	0.429 8	0.110 8

$\sigma^2(a_2)$, $\sigma^2(x_1-q)$ and $\sigma^2(f_d)$ are gotten by simulation on the passive suspension based on ODE3 solving method of Matlab software listed in Tab. 3. According to Eq. (9), Tab. 1 and Tab. 3, β_1, β_2, δ_1 and δ_2 are obtained in Tab. 4.

Tab. 3 $\sigma^2(a_2)$, $\sigma^2(x_1-q)$ and $\sigma^2(f_d)$

$\sigma^2(a_2)/(\mathrm{m}\cdot\mathrm{s}^{-2})^2$	$\sigma^2(x_1-q)/\mathrm{m}^2$	$\sigma^2(f_d)/\mathrm{m}^2$
4.516 2	$1.847\ 5\times10^{-5}$	$1.557\ 7\times10^{-4}$

Tab. 4 Proportional coefficients and weights

Coefficient	Value	Weight	Value
β_1	2 444	δ_1	105 060
β_2	27 081	δ_2	3 000.6

2 Optimization and design of PID controller

2.1 Design of PID controller

The structure of PID controller for ASWEES is shown in Fig. 2, and its output is

$$F_p = k_p e + k_i \int e\mathrm{d}t + k_d \frac{\mathrm{d}e}{\mathrm{d}t} \tag{11}$$

$$e = r - y \tag{12}$$

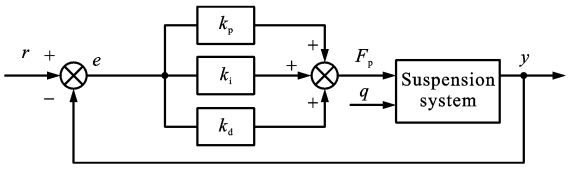

Fig. 2 Structure of PID controller

Where F_p is the control force of ASWEES based on PID control; k_p, k_i and k_d are the proportional gain, the integral gain and the derivative gain respectively; e is the error input of PID controller; r is the desired acceleration of sprung mass; y is the acceleration output of sprung mass and equals $\ddot{x}_2$.

2.2 Optimization of PID control parameters

Genetic algorithm (GA) is chosen as the optimizing method for k_p, k_i and k_d of PID controller for ASWEES[18]. During the optimization procedure, GA iteratively manipulates the populations of the chromosomes using reproduction, crossover and mutation operations, and evaluates the suitability of each solution using a fitness function. Here, the optimization objective function J is taken as the fitness function. The chromosomes with good fitness are carried forward into the next generation and are subsequently used as the basis for generating new and improved solutions. The search procedure continues iteratively until the specified termination conditions have been satisfied. Here, the termination conditions are that the solutions with desired fitness are satisfied for the specified numbers of generations. The flow chart for the optimization based on GA is shown in Fig. 3.

The optimization procedure is carried out by simulation. Simulation time length is set as 40 s and ODE3 solving method is employed. c_0 is set as 10^4 N·s·m^{-1} to decrease the consuming power of basal damping and to insure a good ride comfort. That is to say that the suspension damping ratio is equal to 0.1.

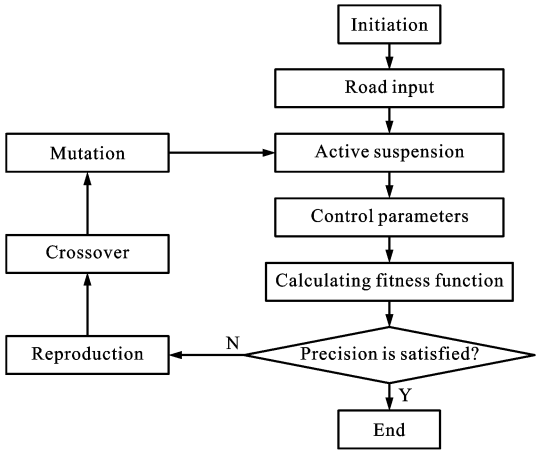

Fig. 3 Optimization flow of PID controller parameters

GA optimizing parameters and PID controller parameters are listed in Tab. 5. *J*-*G* (number of generation) curve is shown in Fig. 4. When the optimizing generation reaches 27, the optimum value of J is obtained and equals 4.580 9. The optimizing results are k_p=760.556, k_i=116 410, and k_d=0.003 2.

Tab. 5 Parameter settings

Parameter	Value	Parameter	Value
Max number of generation	50	Mutation rate	0.017 5
Initial population size	60	Scope of k_p	[0, 20 000]
Crossover rate	0.7	Scope of k_i	[0, 200 000]
Generation gap	0.9	Scope of k_d	[0, 10]

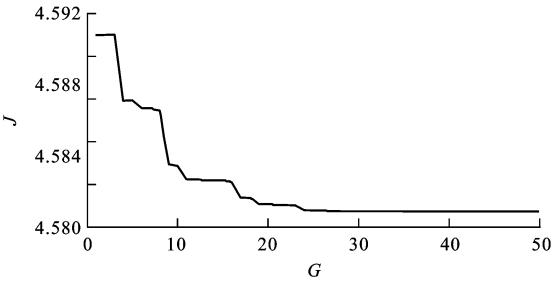

Fig. 4 *J*-*G* curve

3 Design of LQG controller

3.1 LQG controller

The standard form of J is expressed as follow

$$J = \frac{1}{T}\int_0^T (\boldsymbol{X}^{\mathrm{T}}\boldsymbol{Q}\boldsymbol{X} + \boldsymbol{U}^{\mathrm{T}}\boldsymbol{R}\boldsymbol{U} + 2\boldsymbol{X}^{\mathrm{T}}\boldsymbol{N}\boldsymbol{U})\mathrm{d}t \tag{13}$$

$$\boldsymbol{N} = \begin{bmatrix} 0 & \frac{k_2}{m_2^2} & -\frac{k_2}{m_2^2} & \frac{c_0}{m_2^2} & -\frac{c_0}{m_2^2} \end{bmatrix}^{\mathrm{T}}$$

$$\boldsymbol{R} = \begin{bmatrix} \frac{1}{m_2^2} \end{bmatrix}$$

$$\boldsymbol{Q} = \begin{bmatrix} \delta_1 & -\delta_1 & 0 & 0 & 0 \\ -\delta_1 & \delta_1+\delta_2+\frac{k_2^2}{m_2^2} & -\delta_2-\frac{k_2^2}{m_2^2} & \frac{k_2 c_0}{m_2^2} & -\frac{k_2 c_0}{m_2^2} \\ 0 & -\delta_2-\frac{k_2^2}{m_2^2} & \delta_2+\frac{k_2^2}{m_2^2} & -\frac{k_2 c_0}{m_2^2} & \frac{k_2 c_0}{m_2^2} \\ 0 & \frac{k_2 c_0}{m_2^2} & -\frac{k_2 c_0}{m_2^2} & \frac{c_0^2}{m_2^2} & -\frac{c_0^2}{m_2^2} \\ 0 & -\frac{k_2 c_0}{m_2^2} & \frac{k_2 c_0}{m_2^2} & -\frac{c_0^2}{m_2^2} & \frac{c_0^2}{m_2^2} \end{bmatrix}$$

According to modern control theory, the minimum of J can be obtained when the control force is

$$F_1 = -\boldsymbol{R}^{-1}(\boldsymbol{S}\boldsymbol{B} + \boldsymbol{N})^{\mathrm{T}}\boldsymbol{X} \tag{14}$$

$\boldsymbol{S}$ is the solution of Ricatti equation as follow

$$(\boldsymbol{S}\boldsymbol{A})^{\mathrm{T}} + \boldsymbol{S}\boldsymbol{A} - (\boldsymbol{S}\boldsymbol{B}+\boldsymbol{N})\boldsymbol{R}^{-1}(\boldsymbol{S}\boldsymbol{B}+\boldsymbol{N})^{\mathrm{T}} + \boldsymbol{Q} = \boldsymbol{0} \tag{15}$$

F_1 is usually written as follow

$$F_1 = -\boldsymbol{Y}\boldsymbol{X} \tag{16}$$

Where $\boldsymbol{Y}$ is the feedback gain matrix of LQG controller and can be obtained by using LQR function of Matlab software as follow

$$(\boldsymbol{Y}, \boldsymbol{S}, \boldsymbol{E}) = L(\boldsymbol{A}, \boldsymbol{B}, \boldsymbol{Q}, \boldsymbol{R}, \boldsymbol{N}) \tag{17}$$

Where $\boldsymbol{E}$ is the system eigenvector; $L(\cdot)$ is LQR function.

3.2 Parameters of LQG controller

Eqs. (15)-(17) show that c_0 influences F_1. In addition, c_0 influences the power consuming of ASWEES. So it is necessary to investigate the influence of c_0 on the performance and power consuming of ASWEES. $\boldsymbol{A}$ and $\boldsymbol{Q}$ can be written as follows

$$\boldsymbol{A} = \boldsymbol{A}_0 + \boldsymbol{R}^{-1}\boldsymbol{B}\boldsymbol{N}^{\mathrm{T}} \tag{18}$$

$$\boldsymbol{Q} = \boldsymbol{Q}_0 + \boldsymbol{R}^{-1}\boldsymbol{N}\boldsymbol{N}^{\mathrm{T}} \tag{19}$$

$$\boldsymbol{A}_0 = \begin{bmatrix} -2\pi f_0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 \\ \frac{k_1}{m_1} & -\frac{k_1}{m_1} & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \end{bmatrix} \tag{20}$$

$$\boldsymbol{Q}_0 = \begin{bmatrix} \delta_1 & -\delta_1 & 0 & 0 & 0 \\ -\delta_1 & \delta_1+\delta_2 & -\delta_2 & 0 & 0 \\ 0 & -\delta_2 & \delta_2 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \end{bmatrix} \tag{21}$$

Taking Eqs. (18) and (19) into Eq. (15), there is an equation as follow

$$[\boldsymbol{S}(\boldsymbol{A}_0+\boldsymbol{R}^{-1}\boldsymbol{B}\boldsymbol{N}^{\mathrm{T}})]^{\mathrm{T}} + \boldsymbol{S}(\boldsymbol{A}_0+\boldsymbol{R}^{-1}\boldsymbol{B}\boldsymbol{N}^{\mathrm{T}}) - (\boldsymbol{S}\boldsymbol{B}+\boldsymbol{N})\boldsymbol{R}^{-1}(\boldsymbol{S}\boldsymbol{B}+\boldsymbol{N})^{\mathrm{T}} + \boldsymbol{Q}_0 + \boldsymbol{R}^{-1}\boldsymbol{N}\boldsymbol{N}^{\mathrm{T}} = \boldsymbol{0}$$

It is simplified as follow

$$\boldsymbol{A}_0^{\mathrm{T}}\boldsymbol{S}^{\mathrm{T}} + \boldsymbol{S}\boldsymbol{A}_0 - \boldsymbol{R}^{-1}\boldsymbol{S}\boldsymbol{B}(\boldsymbol{S}\boldsymbol{B})^{\mathrm{T}} + \boldsymbol{Q}_0 = \boldsymbol{0} \tag{22}$$

Taking Eqs. (14), (18) and (19) into Eq. (13), there is an equation as follow

$$\boldsymbol{X}^{\mathrm{T}}\boldsymbol{Q}\boldsymbol{X} + \boldsymbol{U}^{\mathrm{T}}\boldsymbol{R}\boldsymbol{U} + 2\boldsymbol{X}^{\mathrm{T}}\boldsymbol{N}\boldsymbol{U} = \boldsymbol{X}^{\mathrm{T}}[\boldsymbol{Q}_0 + \boldsymbol{R}^{-1}\boldsymbol{N}\boldsymbol{N}^{\mathrm{T}} + \boldsymbol{R}^{-1}(\boldsymbol{S}\boldsymbol{B}+\boldsymbol{N})\boldsymbol{R}\boldsymbol{R}^{-1}(\boldsymbol{S}\boldsymbol{B}+\boldsymbol{N})^{\mathrm{T}} - 2\boldsymbol{N}\boldsymbol{R}^{-1}(\boldsymbol{S}\boldsymbol{B}+\boldsymbol{N})^{\mathrm{T}}]\boldsymbol{X}$$

It is simplified as follow

$$\boldsymbol{X}^{\mathrm{T}}\boldsymbol{Q}\boldsymbol{X} + \boldsymbol{U}^{\mathrm{T}}\boldsymbol{R}\boldsymbol{U} + 2\boldsymbol{X}^{\mathrm{T}}\boldsymbol{N}\boldsymbol{U} = \boldsymbol{X}^{\mathrm{T}}[\boldsymbol{Q}_0 + \boldsymbol{R}^{-1}\boldsymbol{S}\boldsymbol{B}(\boldsymbol{S}\boldsymbol{B})^{\mathrm{T}}]\boldsymbol{X} \tag{23}$$

Because k_2 and c_0 do not appear in Eq. (22), $\boldsymbol{S}$ is irrelative to k_2 and c_0. Similarly, Eqs. (13) and

(23) show the responses of ASWEES based on LQG control are irrelative to k_2 and c_0 too. Smaller is c_0, smaller is its power consuming. So c_0 is set as 0. According to Eq. (17), $\boldsymbol{Y}$ is obtained as follow

$$\boldsymbol{Y}=10^5(3.475\ 6,-0.738\ 9,-2.311\ 1,\\ -0.166\ 2,0.549\ 3)$$

4 Performance and energy availability of ASWEES

Based on the results of sections 2-3, the evaluating indexes of performance and energy availability of ASWEES based on optimized PID control and LQG control are gotten. J, P_s, P_a, $\sigma(a_2)$, $\sigma(x_1-q)$ and $\sigma(f_d)$ are listed in Tab. 6. $\sigma(a_2)$, $\sigma(x_1-q)$ and $\sigma(f_d)$ are the mean square roots of a_2, x_1-q and f_d respectively. J-t curves are shown in Fig. 5. P-t curves of ASWEES based on optimized PID control are shown in Fig. 6. P-t curves of ASWEES based on optimized LQG control are shown in Fig. 7. W_s/W_a-t curves are shown in Fig. 8.

Tab. 6 Data of $\sigma(a_2)$, $\sigma(x_1-q)$, $\sigma(f_d)$, J, P_s and P_a

Parameter	Optimized PID control	LQG control
$\sigma(a_2)$ /(m·s^{-2})	1.228 8	1.380 3
$\sigma(f_d)$/m	0.014 2	0.012 9
$\sigma(x_1-q)$/m	0.004 8	0.004 4
J	4.580 9	4.428 6
P_s/kW	−1.179 2	−2.919 6
P_a/kW	0.068 4	0.128 9

Tab. 6 and Fig. 5 show that J values of ASWEES based on LQG control and optimized PID control are 4.428 6 and 4.580 9 respectively, it is to say that J of ASWEES based on LQG control is 3.32% smaller than that of ASWEES based on optimized PID control. So the performance of ASWEES based on LQG control is weakly better than that of the other.

Figs. 6-8 show that the reclaiming energy powers and works in the semi-active control mode are bigger than the energy consuming powers and works in the active control mode. P_s is strongly bigger than P_a for ASWEES based on LQG control. According to Tab. 6, $\left|\frac{P_s}{P_a}\right|$ values of ASWEES based on optimized PID control and LQG control are

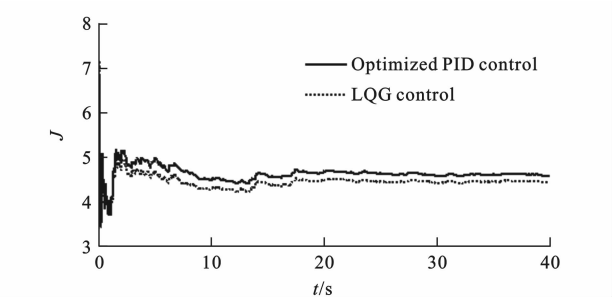

Fig. 5 J-t curves

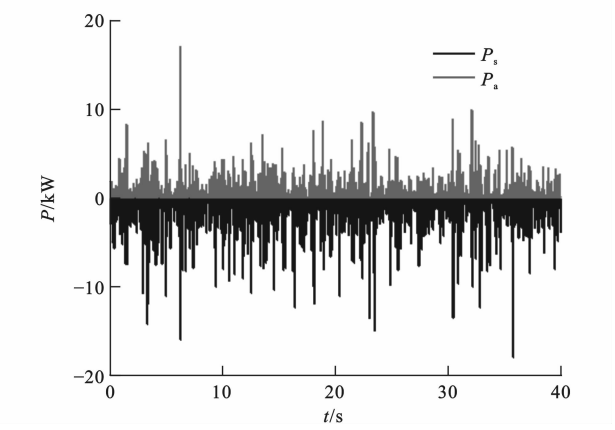

Fig. 6 P-t curves based on optimized PID control

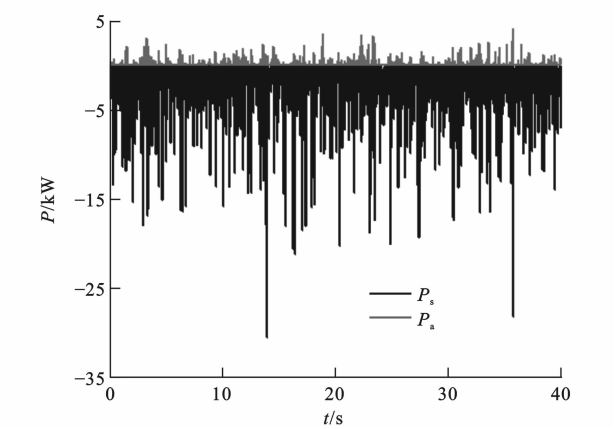

Fig. 7 P-t curves based on LQG control

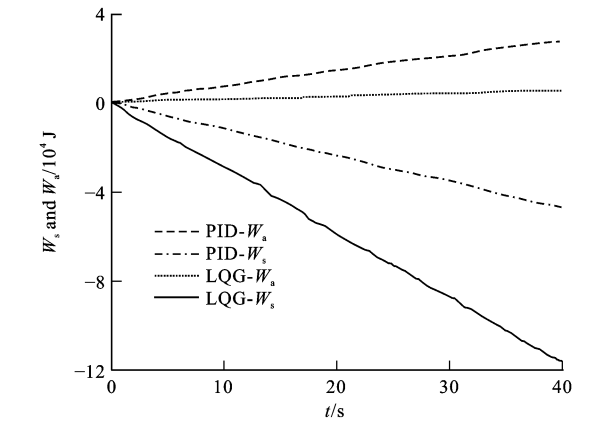

Fig. 8 Curves of W_s/W_a-t

obtained and equal to 17.15 and 226.33 respectively. So the energy availabilities of two ASWEESs meet the demand, and the energy availability of ASWEES based on LQG control is much better than that of the other.

5 Conclusions

The absolute ratio of mean power reclaimed in the semi-active control mode divided by that consumed in the active control mode is proposed as the energy availability index of ASWEES. Bigger is the index, better is the energy availability. The parameters of PID controller are optimized according to GA with suspension quadratic performance index taken as the fitness function when the suspension damping ratio is 0.1. The suspension performance of ASWEES based on LQG control is weakly better than that of ASWEES based on optimized PID control. The energy availabilities of two ASWEESs meet the demand, and the energy availability of ASWEES based on LQG control is much better than that of the other.

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