Design and Performance Analysis of ISD Suspension Based on New Mechanical Network Isolation Theory

Jun Yang, Long Chen, Xiaofeng Yang & Yujie Shen

School of Automotive and Traffic Engineering, Jiangsu University, Jiangsu Zhenjiang, 212013, China

Keywords: inerter, ISD suspension, coupling relationship, quantum genetic algorithm, matlab / simulink.

Abstract. By analysing the vibration response of two mutual coupling structures between three basic elements ‘spring, damper and inerter’ on a single degree of freedom system. Focusing on the vibration isolation effect, the optimum coupling relationship of ‘spring, damper and inerter’ three basic components applied in vehicle suspensions was studied. According to that, three kinds of ISD (Inerter-Spring- Damper) suspension structures were put forward. To verify the validity of the designed structures, building the quarter vehicle ISD suspension model of three chosen structures in matlab/simulink. In order to avoid the traditional genetic algorithm falling into local optimum, using quantum genetic algorithm to optimize the spring stiffness, damping coefficient and inertance in terms of vehicle body acceleration, suspension travel and dynamic tire load. Simulation results show that the performance of vehicle body acceleration mean square root, suspension travel mean square root and tire dynamic load mean square root were decreased at the same time compared to traditional passive suspension. Furthermore, the optimum coupling relationship of ‘spring, damper and inerter’ three basic elements applied to vehicle suspension is that spring and damper are available in series and parallel, inerter and spring should be in parallel, inerter and damper should be in series.

Introduction

Suspension is one of the most important assemblies on the vehicle. It connects the vehicle body and the wheels together elastically, and has great influence on ride comfort, handle stability. The structure, stiffness and damping coefficient of the traditional passive suspension are relatively fixed, these limit the further improve of the vehicle’s performance. Although the active/semi-active suspension can achieve real-time adjustment to the suspension’s performance, the complex structure, high cost and the difficulty to control have limited their further application.

In 2002, Smith, a scholar of university of Cambridge, put forward the concept of inerter and the realized device based on mechanical-electrical analogy theory, and then applied it to the field of vibration isolation, found vehicle suspensions used the ISD structures can improve the performance of vibration isolation of the vehicle, which caused the attention of the vehicle engineering.

This study doing the vibration response analysis of the six kinds of structures coupled by two from the three elements (inerter, spring, and damper) under the single degree of freedom system, three kinds of vehicle ISD suspension structures were put forward. The parameters of the ISD suspension structures were optimized by quantum genetic algorithm in terms of three evaluation indexes for vehicle performances. Quarter vehicle suspension model was built in the matlab/simulink. Through the simulation, the optimum coupling relationship of ‘spring, damper and inerter’ three basic elements applied to vehicle suspension was obtained.

New mechanical network vibration isolation mechanism analysis

Choosing two elements from the ‘spring, damper and inerter’ three basic elements to couple, 6 kinds of structures were get: spring and damper in parallel, spring and damper in series, spring and inerter in parallel, spring and inerter in series, damper and inerter in parallel, damper and inerter in series. The single degree of freedom system diagram is presented in Figure 1.

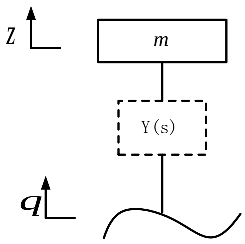

Fig. 1 single degree of freedom system

According to Figure 1, dynamic equation under the Laplace change can be obtained as equation 1 using complex domain mechanical impedance method.

$$ms^2Z + sY(s)(Z - Q) = 0 \tag{1}$$

Amplitude transfer ratio is obtained by mathematical change.

$$\frac{Z}{Q} = \frac{sY(s)}{ms^2 + sY(s)} \tag{2}$$

Where, z is the vertical displacement of mass m, q is the vertical displacement of the given excitation; Z, Q are the Laplace transforms of z,q, Y (s) is the complex domain mechanical impedance.

Numerical calculation program was written by Matlab software, the simulation frequency range is 0.1 ~ 100 Hz, the amplitude transfer ratio of spring and damper in series and in parallel were shown in Figure 2, the amplitude transfer ratio of spring and inerter in series and in parallel were shown in Figure 3, the amplitude transfer ratio of damper and inerter in series and in parallel were shown in Figure 4 by simulation.

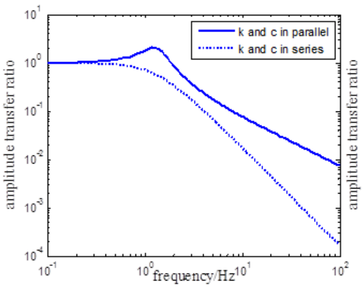

Fig. 2 Amplitude transfer comparison digram of the series – parallel spring and damper

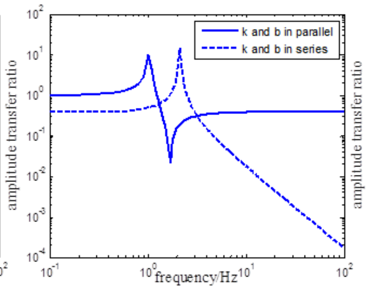

Fig. 3 Amplitude transfer comparison diagram of the series – parallel spring and inerter

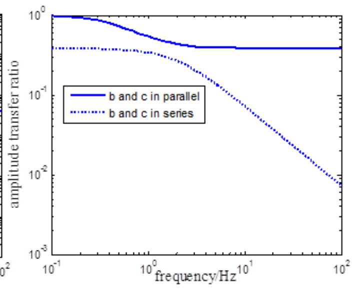

Fig. 4 Amplitude transfer comparison diagram of the series – parallel inerter and damper

From Figure 2, spring and damper in parallel is the usual structure of traditional passive suspension, except in vehicle body working frequency, it has good vibration isolation effect in other frequency range. Spring and damper in series has good vibration isolation effect throughout the whole simulation frequency domain. From Figure 3, the amplitude transfer ratio of inerter and damper in parallel within the frequency range of 1 ~ 100 Hz is smaller than 1, which means it has damping effect.Vehicle body working frequency range is generally 1 ~ 2 Hz[6].However, the amplitude transfer ratio of inerter and damper in series at the vehicle body working frquency is larger than1,which means it amplifies the effect of excitation, the damping effect is obviously superior to the parallel structure within 2 ~ 100 Hz.Therefore, inerter and damper in parallel and in series have their own characteristics on vibration isolation. From Figure 4, the amplitude transfer ratios of inerter and damper in series and in parallel are both smaller than 1 within the scope of the simulation frequency. But the vibration isolation effect of inerter and damper in series is obviously better than in parallel, and significantly increases with the increase of frequency.

Therefore, focusing on vibration isolation effect, spring and damper can be in series and in parallel, inerter and damper in series should be better. For further study of the best coupling relationship of spring and inerter on vehicle suspension application, there are four structures accordingly. The three structures in virtual box cannot be directly applied to vehicle suspension, a main spring is added in parallel for avoiding passive mechanical device failing to bear overload.

According to spring and damper can be in series and in parallel, inerter and damper should be in series ,inerter and spring are in parallel, two kinds of ISD were obtained as Figure5. According to spring and damper can be in series and in parallel, inerter and damper should be in series ,inerter and spring are in series, two kinds of ISD were obtained as Figure 6.

Chen Long and Yang Xiaofeng [2], have studied S3 structure used in vehicle suspension, the effect is not ideal. Therefore, in the following work, the optimum coupling relationship of ‘spring, damper and inerter’ three basic components applied in vehicle sususpension was studied through the comparative analysis of the rest three ISD structures S1, S2 and S4.

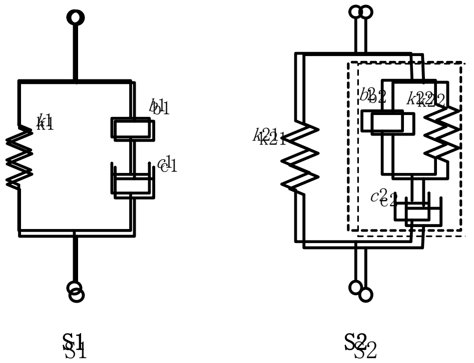

Fig. 5 ISD sturcture (parallel)

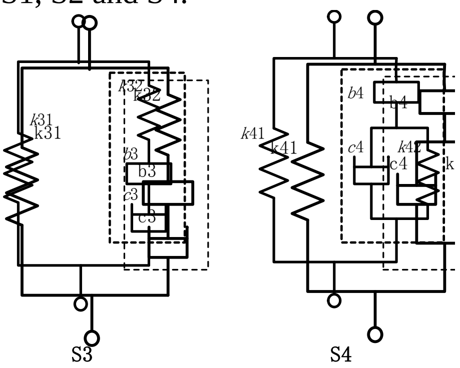

Fig. 6 ISD structure (series)

Suspension system dynamic model

A quarter vehicle suspension model was built as Figure 7. The dynamic equation under the Laplace transform of the model is:

$$\begin{cases} m_s s^2 Z_s + sY(s)(Z_s - Z_u) = 0 \\ m_u s^2 Z_u - sY(s)(Z_s - Z_u) + k_t(Z_u - Z_r) = 0 \end{cases} \tag{3}$$

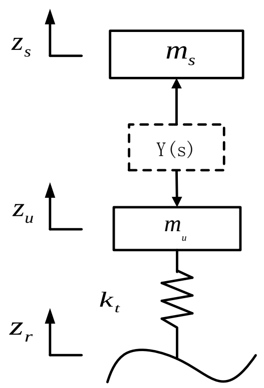

Fig.7 Diagram of quarter-vehicle suspension model

Where, m_s is the sprung mass,m_u is the unsprung mass; k_t is the tire stiffness,Y (s) is the complex domain mechanical impedance of ISD suspension, z_s is the displacement of sprung mass,z_u is the displacement of unsprung mass,z_r is the displacement of the road input. Zs, Zu, Zr are respectively the Laplace transform of z_s, z_u, z_r.

The complex domain mechanical impedance of S1,S2 and S4 are as follows:

$$Y_1(s) = \frac{k_1}{s} + \frac{1}{b_1 s + c_1} \quad Y_2(s) = \frac{k_{21}}{s} + \frac{1}{\dfrac{1}{b_2 s + k_{22}/s} + \dfrac{1}{c_2}} \quad Y_4(s) = \frac{k_{41}}{s} + \frac{1}{\dfrac{1}{1/c_4 + s/k_{42}} + \dfrac{1}{b_4}}$$

Where, k_{i1} is the suspension main spring stiffness, k_{i2} is the deputy spring suspension stiffness, c_i is the damping coefficient, b_i is the inertance, i=1,2,4.

ISD suspension parameters optimization

For comparing the comprehensive performance of the vehicle ISD suspension with the traditional passive suspension, a mature car suspension was chosen as a uniform suspension model. Parameters are as follows: Sprung mass m_s is 320kg, unspring mass m_u is 45kg, tire stiffness k_t is 22kN·m^{-1}, spring stiffness k is 19 kN·m^{-1} and damping coefficient c is 1300N·s·m^{-1}.

Quantum genetic algorithm is a genetic algorithm based on quantum computing and better results than conventional genetic algorithm can be achieved.

First, the traditional passive suspension vehicle body acceleration root mean square BA_{pas}, suspension travel root mean square SWS_{pas}, tyre dynamic load root mean square DTL_{pas} under random road input were obtained by time domain simulation. The ISD suspension vehicle body acceleration root mean square *BA*, suspension travel root mean square *SWS*, tire dynamic load root mean square *DTL* were obtained under the same road input.

The Quantum genetic algorithm fitness function [10] is shown in Equation 4:

$$F = -\left(\frac{BA}{BA_{pas}} + \frac{SWS}{SWS_{pas}} + \frac{DTL}{DTL_{pas}}\right) \tag{4}$$

S1, S2, S4 ISD suspension optimal parameters were obtained using quantum genetic algorithm in matlab as shown in Table 1:

Table 1 Optimal Parameters of ISD Suspension

Suspension type	parameters	values
S1	Spring stiff k_1/ kN·m^{-1}	12.023
	Inertance b_1/kg	10
	Damping coefficient c$_1$/N·s·m^{-1}	1724
S2	Main spring stiff k_{21}/ kN·m^{-1}	18
	Deputy spring stiff k_{22}/ kN·m^{-1}	10
	Inertance b_2/kg	998
	Damping coefficient c_2/N·s·m^{-1}	2055
S4	Main spring stiff k_{41}/ kN·m^{-1}	22
	Deputy spring stiff k_{42}/ kN·m^{-1}	10
	Ineterance b_4/kg	217
	Damping coefficient c_4/N·s·m^{-1}	1067

Simulation analysis

The performance of suspension system in terms of vehicle body acceleration power spectrum density, suspension travel power spectrum density and tire dynamic load power spectrum density was analysed in frequency domain. Random road input model [6] was given as the following:

$$\dot{z}_r(t) = -2\pi f_0 z_r(t) + 2\pi\sqrt{G_0 u}\,w(t) \tag{5}$$

Where, the cut-off frequency f_0 is 0.01 Hz, road roughness coefficient G_0 is 5×10^{-6} m^{3}cycle^{-1}, w (t) is integral white noise, the speed u is 20 m/s.

Performance analysis of S1, S2, S4 vehicle ISD suspensions were done within the frequency range of 0 ~ 15 Hz. And select speed 20 m/s, vehicle body acceleration power spectrum density, suspension travel power spectrum density and tire dynamic load power spectrum density compared with the traditional passive suspension were shown in Figure 8.

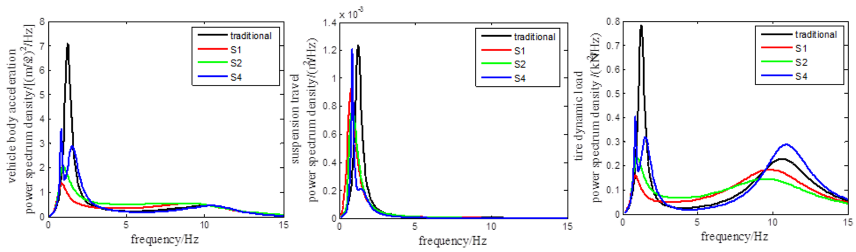

Fig.8 Comparison diagram of vehicle performance index

From Figure 8, the vehicle body acceleration, suspension travel and tire dynamic load power spectrum density values of S1, S2, S4 vehicle ISD suspensions were obviously decreased compared with the traditional passive suspension within frequency range of 0 ~ 15 Hz. Especially in the vehicle body working frequency around 1Hz, the peak decline is more noticeable, the shock and vibration from the road surface is isolated effectively and the ride comfort of vehicle is improved. Obviously, the performance of S1, S2 vehicle ISD suspension is better than the S4 vehicle ISD suspension, in particular, suspension travel power spectrum density of the S4 vehicle ISD suspension was not improved obviously compared with traditional passive suspension, and a resonance peak was added. However, the performance of suspension travel of S1, S2 vehicle ISD suspension was improved significantly traditional passive suspension, especially in body working frequency around 1Hz. Moreover there is no any other resonance peaks added.

For more clearly comparing the performance of S1, S2 vehicle ISD suspension with S4 vehicle ISD suspension. Vehicle body acceleration root mean square values (*BA*), suspension travel root mean square values (*SWS*), tire dynamic load root mean square values (*DTL*) of traditional passive suspension and S1, S2, S4 vehicle ISD suspension under the speed of 10 m/s, 20 m/s, 30 m/s were shown in Table 2

Table 2 Mean Square Root of Suspension Performance Index

Suspension type	Speed m/s^2	*BA* m/s^2	*SWS* m	*DTL* kN
	10	1.7489	0.0185	0.8015
traditional	20	2.9412	0.0311	1.3479
	30	3.9865	0.0421	1.8270
	10	1.4612	0.0177	0.7278
S1	20	2.4574	0.0297	1.2240
	30	3.3307	0.0403	1.6590
	10	1.6595	0.0165	0.7253
S2	20	2.7910	0.0277	1.2198
	30	3.7829	0.0376	1.6543
	10	1.5989	0.0184	0.7978
S4	20	2.6891	0.0309	1.3417
	30	3.6447	0.0419	1.8185

The comparison in Table 2 shows the vehicle body acceleration root mean square value of S1 vehicle ISD suspension drops 5.0%, suspension travel root mean square value drops 10.8%,tire dynamic load root mean square value drops 9.5%, the vehicle body acceleration root mean square value of S2 vehicle ISD suspension drops 16.4%, suspension travel root mean square value drops 4.5%,tire dynamic load root mean square value drops 9.1%, the vehicle body acceleration root mean square value of S4 vehicle ISD suspension drops 8.6%, suspension travel root mean square value drops only 0.64%,tire dynamic load root mean square value drops only 0.46% compared to the traditional passive suspension. The above datas demonstrated that the performance of S1, S2 vehicle ISD suspension is superior to S4 vehicle ISD suspension.

From all above analysis, the optimum coupling relationship of ‘spring, damper and inerter’ three basic components applied to vehicle susupension is that spring and damper are available in series and parallel, inerter and spring should be in parallel, inerter and damper should be in series.

Conclusions

(1) Focusing on the vibration isolation effect, the optimum coupling relationship of ‘spring, damper and inerter’ three basic components applied to vehicle suspensions was studied. Three ISD structures were proposed to apply to vehicle suspension, the simulation results show that the spring and damper are available in series and in parallel, inerter and spring should be in parallel, inerter and damper should be in series.

(2) Quantum genetic algorithm is a genetic algorithm based on quantum computing and applied to vehicle ISD suspension parameters optimization, the results of the optimized parameters used in the vehicle suspension were satisfactory.

(3) The ISD suspension structures put forward based on analysing the vibration response of two mutual coupling structures from three basic elements ‘spring, damper and inerter’ on a single degree of freedom system were simple and effective. The contradiction between the ride comfort and handle stability of the traditional passive suspension can be effectively relieved.

Acknowledgements

The research work was supported by China Postdoctoral Foundation under Grant No. 2014M561591, ‘Six Talents Peak’ project of Jiangsu Provincial under Grant No.JNNB-023 and Postdoctoral Foundation of Jiangsu Priovincial under Grant No.1402098C.

References

[1]Papagergiou C, Smith M C.Positive real synthesis using matrix inequalities for mechanical networks: application to vehicle suspension [J]. *IEEE Transaction on Control Systems Technology*, 2006, 14(3):423-434.

[2]Chen Long,Yang Xiao-feng,Wang Ruo-chen.Design and performance study of vehicle passive suspension based on two-element inerter-spring-damper structure vibration isolation mechanism[J]. Journal of Vibration and Shock, 2013, 4(6):90-95.

[3]Smith M C.Synthesis of mechanical networks: the inerter [J].IEEE Transaction on Auto Control, 2002, 47(10):1648-1662.

[4]Smith MC, Wang FC.Performance benefits in paasive vehicle suspension employing inerters [J].Vehicle System Dynamics, 2004, 42(4):235-257.

[5]Chen Long,Zhang Xiao-liang,Jiang Hao-bin.Vehicle Suspension System Employing Inerter Based on Electric al-mechanical Analogy Theory[J].China Mechanical Engineering,2009,20(10): 1248-1251.

[6]Yu Fan, Lin Yi.Vehicle system dynamics [M].Beijing:Machinery Industry Press,2008:146-149

[7]Chen Long,Shen Yu-jie,Yang Xiao-feng.Design and experiment of vehicle suspension based inerter-spring structure[J].Journal of Vibration and Shock, 2014(22):83-87.

[8]Chen Long,Yang Xiao-feng,Wang Ruo-chen.A Study on the Performances of Vehicle Passive Suspension with Modified Inerter-spring-damper Three-element Structure[J].Automotive Engineering,2014,36(3):340-345.

[9]Yang Xiao-feng, Shen Yu-jie, Chen Long.Design and Performance Analysis of Vehicle ISD Suspension Based on Dynamic Vibration Absorber Theory [J].Automotive Engineering, 2014, 36(10):1311-1315

[10]YangXiao-feng,ChenLong, ShenYu-jie.Analysis on vehicle passive inerter-spring-damper suspension employing simple three-element structure[J]. Journal of Machine Design, 2013, 30(12):42-46

[11]Du Fu, Mao Ming, Chen Yi-jie.Structure design and performance analysis of inerter-spring-damper suspension structure based on dynamic model and parameter optimization [J]. Journal of Vibration and Shock, 2014, 33(6):59-65