Analyses of Vehicle Vibration Based on Virtual Reality

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Abstract-*This paper presents the idea for analyses of vehicle vibration based on Virtual Reality, whose setup block diagram is given. Using the World Tool Kid (WTK), the virtual proving ground is established and can be interacted with it. Also, a conception on non-stationary random process power spectral density function (PSD) is presented and it is proved that the rough road PSD is non-stationary random process Wiener process PSD. For the purpose of the vehicle vibration analyses with engine and random road excitations, a five- degree of freedom model is considered for half the vehicle and simulation analyses is performed under the help of the mechanical system simulation code ADAMS. Simulation results show that the Vertical acceleration PSD predicted using the virtual vehicle and road are in close agreement with that obtained using the actual vehicle and road.*

Keywords: *Virtual Reality (VR), vehicle vibration,* power *spectral density (PSD), simulation,*

1 Introduction

To improve the ride quality, the vibrations of a vehicle body should be reduced. As well known, the low-frequency vibrations are mainly caused by the disturbance from the road. Various kinds of active/passive controlled suspension systems that absorb vertical vibration of the chassis to reduce ride discomfort have been proposed. Most of these studies focus on the vibration of the vehicle chassis, seats and passenger bodies that depend mainly on the mechanical characteristics of vehicles and road paving [1]. But the relatively high-frequency (20-40Hz) vibrations, which are mainly caused by the engine idle speed, may induce uncomfortable shake and noise in the vehicle cabin. The engine vibrations are mainly caused by the reciprocating mechanism in the engine. The frequency of these vibrations is determined by the engine speed. The engine vibrations are transmitted to the body structure through the engine mounts. These vibrations excite the vibration modes of the vehicle body panels to induce shake and noise. On the other hand, the velocity fluctuation is an important factor of ride discomfort. However, the influence of the velocity fluctuation, the engine and driveline vibrations on vehicle body vibration have seldom been discussed in the ride comfort studies [2-3].

As the vehicle is a complex multi-body system, whose subsystems have vibrations in respective form even couple with each other to influence full vehicle vibration. To study vehicle vibration effectively, considering all excitations is essential for the simulation analyses on full vehicle vibration by means of the modern simulation technology.

Virtual Reality (VR) is the computer-aided simulation environment of a 3-D model that one can interact with in order to get a better sense of the project. The virtual environment created by computer, is a kind of simulation of interactive vision field, making users feel as if they were in the environment in person, through acting on users by vision, hearing and touching etc. Its characteristics are the immersion, interaction and imagination. VR has the potential of revolutionizing design and manufacturing in industries. The proposal predicted savings in time and money, better market response and better products.

This paper is focused on the performance analyses and assessment for full vehicle vibration in virtual reality environment, which will become more efficient through the simulation results of the virtual prototype in vehicle design.

2 The system design for vehicle vibration simulation

The analyses system of vehicle vibration based on virtual reality consists of several of modules such as input module, virtual test module and analyses module etc, whose setup block diagram is shown in Figure 1.

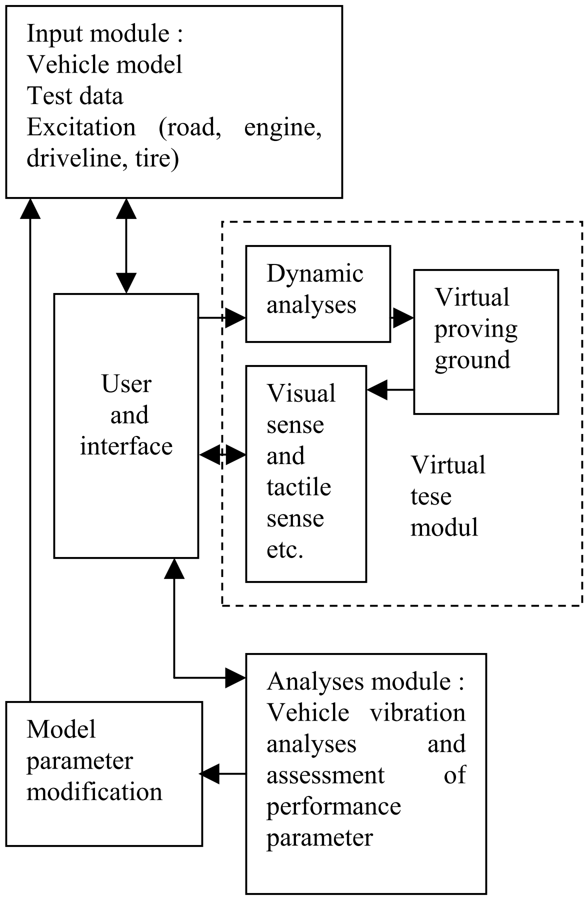

Figure 1. Block diagram of system setup

Input module: supply vehicle model, random excitation (such as rough road, engine, driveline and tire), actual vehicle test data etc.

Dynamic analyses module: by ADAMS software and parametric vehicle model, vehicle vibration analyses is performed under road and engine excitation.

Virtual test module: supply living virtual test environment for users and make them immerse into the virtual environment, moreover, get all vibration feelings just as in the real vehicle.

Assessment module: according to all feelings under virtual test environment, vehicle performances are assessed and then vehicle model parameters are modified. Thus, optimal design aim is achieved.

3 Description of the road power spectral density function

Generally, the road irregularity is considered as a steady, ergodic gauss random process. Thus, we often describe road surfaces with the PSD (power spectral density) of a single track and the coherence function of two parallel tracks. In fact, the PSD of road surfaces is a non-stationary random process, whose coherence function and PSD have some relation of correspondence. Through a lot of experiments, PSD of rough road surfaces can be described by the following expression [4-6]:

$$S_q(\omega) = \frac{A}{\omega^2} \tag{1}$$

where ω is length frequency (m^{-1}), A is rough road surfaces coefficient (m^2/m^{-1}).

Suppose a stationary random process $X(t)$, then the power spectral density is:

$$S_X(\omega) = \lim_{T\to\infty} \frac{1}{T} E\left[\left|F_X(\omega,T)\right|^2\right] \tag{2}$$

where $F_X(\omega,T) = \int_{-\infty}^{+\infty} X_T(t)e^{j\omega t}dt$

$$X_T(t) = \begin{cases} X(t) & t \le T \\ 0 & t > T \end{cases}$$

Similarly, suppose a non-stationary random process $B(t)$, then the power spectral density is:

$$S_B(\omega) = \lim_{T\to\infty} \frac{1}{T} E\left[\left|F_B(\omega,T)\right|^2\right] \tag{3}$$

where $F_B(\omega,T) = \int_{-\infty}^{+\infty} X_T(t)e^{j\omega t}dt$, because

$$\begin{aligned} S_B(\omega) &= \lim_{T\to\infty} \frac{1}{T} E\left[\left|F_B(\omega,T)\right|^2\right] \\ &= \lim_{T\to\infty} \frac{1}{T} E\left[F_B(\omega,T)F_B(-\omega,T)\right] \\ &= \lim_{T\to\infty} \frac{1}{T} \int_0^T\int_0^T E\left[B(t)B(s)\right]e^{-j\omega(s-t)}dtds \\ &= \lim_{T\to\infty} \frac{1}{T} \int_0^T\int_0^T R_B(t,s)e^{-j\omega(s-t)}dtds \end{aligned}$$

The above deduction indicates that if there is power spectral density for a non-stationary random process $B(t)$, and then the necessary and sufficient condition is:

$$S_B(\omega) = \lim_{T\to\infty} \frac{1}{T} \int_0^T\int_0^T R_B(t,s)e^{-j\omega(s-t)}dtds \tag{4}$$

Because Wiener process is not stationary process, whose mathematical expectation is zero and coherence function $\sigma^2 \min(t,s)$, according to (4), the power spectral density for Wiener process is:

$$S_B(\omega) = \lim_{T\to\infty} \frac{1}{T} \int_0^T \int_0^T \sigma^2 \min(t,s) e^{-j\omega(s-t)} dtds$$
$$= \sigma^2 \left\{ \frac{2}{\omega^2} - \lim_{T\to\infty} \frac{2\sin\omega T}{\omega^3 T} \right\} = \frac{2\sigma^2}{\omega^2}$$

therefore $$S_B(\omega) = \frac{2\sigma^2}{\omega^2} \quad (5)$$

Clearly, there is the same form between expression (1) and (5). Thus, taking Wiener process as road surfaces signal for time domain is good for virtual vibration analyses on vehicle input. Figure 2. Indicates the simulation random road surfaces by Wiener process.

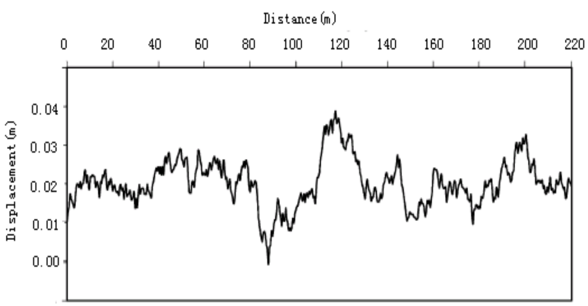

Figure 2. Simulation random road surfaces

4 Description of virtual proving ground (VPG)

4.1 WTK

WTK is an application tool kit used in the virtual environment, created by Sense8 Corporation, and it provides an integrated, complex application developing virtual environment. One of the WTK characteristics is its independent of hardware. It can be run on series of image platforms from the general PC with the graph accelerator to the top grade graph workstation. That means development can be done on the low cost platform, and then the software can be transplanted to the special highly efficient objective computers.

4.2 The establishment of VPG

The establishment of virtual proving ground has follow procedures: One is the establishment of virtual environment (3-D modeling, preprocessing, leading model into virtual environment etc.). The other is the realization of interaction (use of VR tools: 3-D position tracker, 3-D mouse, data clothing, stereo display devices, sensing glove etc.). Virtual Reality software WTK (World Tool Kid) is adopted to establish the virtual proving ground. The flow chart for virtual proving ground modeling is shown as Figure 3. The demonstration of virtual proving ground is shown as Figure 4. [7]

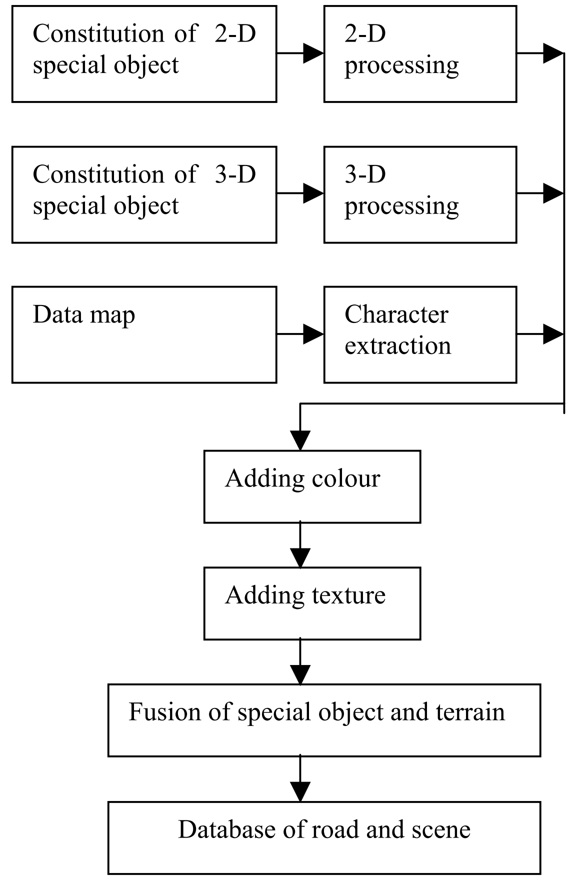

Figure 3. Flow chart for virtual proving ground modeling

Figure 4. Demonstration of virtual proving ground

4.3 The establishment of virtual vehicle

Under the help of the mechanical system simulation code ADAMS, a certain virtual vehicle is built, which consists of some parts such as engine, tires, front and rear suspension, driveline, vehicle body, chassis and so on. (see figure 5, it neglects vehicle body, chair and human being etc.) [8]

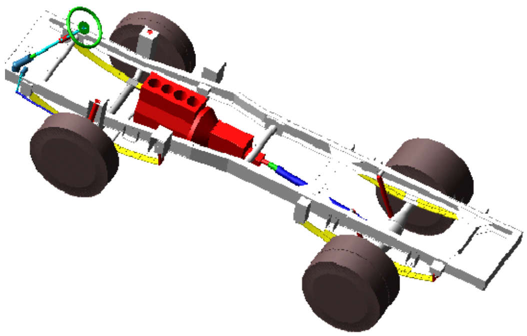

figure 5 virtual vehicle model

5 Dynamic modeling and analyses

5.1 Vehicle model

For the purpose of the full vehicle vibration analyses with engine and random road excitations, a five- degree of freedom model is considered for half the vehicle [5]. The half-vehicle model considered in this paper is shown in Figure 6.

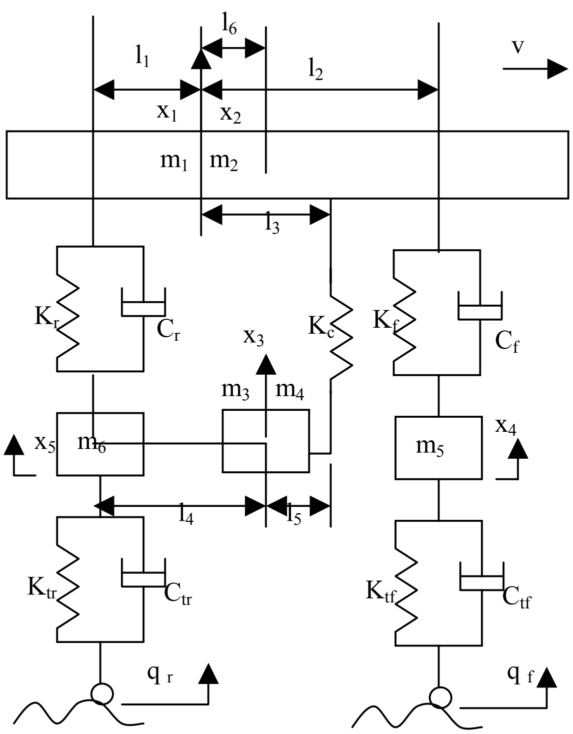

Figure 6. Five-DOF half vehicle model

where m_1 and m_2 are sprung mass and its moment of inertia, m_3 and m_4 are engine mass and its moment of inertia, m_5 and m_6 are unsprung mass of front and rear axle, x_1 and x_2 are the sprung mass displacement and its longitudinal angular displacement, x_3 vertical displacement of the engine, x_4 and x_5 are the unsprung mass displacement of front and rear axle respectively.

According to the five-DOF half vehicle model, we get the motion differential equations in the matrix form, i.e.

$$[M]\{\ddot{x}\}+[C]\{\dot{x}\}+[K]\{x\}=\{F\} \qquad (6)$$

where

$\{x\}=\{x_1,x_2,x_3,x_4,x_5\}^T$;

$\{\dot{x}\}=\{\dot{x}_1,\dot{x}_2,\dot{x}_3,\dot{x}_4,\dot{x}_5\}^T$;

$\{\ddot{x}\}=\{\ddot{x}_1,\ddot{x}_2,\ddot{x}_3,\ddot{x}_4,\ddot{x}_5\}^T$;

$\{F\}=[K_r]\{q\}$;

one order reciprocating inertia force of engine is P_t ,

$P_t = m_A r\omega^2\cos\omega t$;

vehicle input excitations are $\{q\}$,

$\{q\}=\{m_A r\cos\omega t, q_f, q_r\}^T$;

$$[M]=\begin{bmatrix} m_1 & 0 & 0 & 0 & 0 \\ 0 & m_2 & 0 & 0 & 0 \\ 0 & 0 & m_3+\dfrac{m_4}{l_4^2} & 0 & -\dfrac{m_4}{l_4^2} \\ 0 & 0 & 0 & m_5 & 0 \\ 0 & 0 & -\dfrac{m_4}{l_4^2} & 0 & m_6+\dfrac{m_4}{l_4^2} \end{bmatrix}$$

$$[C]=\begin{bmatrix} C_r+C_f & -l_1C_r+l_2C_f & 0 & -C_f & -C_r \\ -l_1C_r+l_2C_f & l_1^2C_r+l_2^2C_f & 0 & -l_2C_f & l_1C_r \\ 0 & 0 & 0 & 0 & 0 \\ -C_f & -l_2C_f & 0 & C_f & 0 \\ -C_r & l_1C_r & 0 & 0 & C_r \end{bmatrix}$$

$$[K]=\begin{bmatrix} K_r+K_c+K_f & -l_1K_r+l_3K_c+l_2K_f & -\frac{l_4+l_5}{l_4}K_c & -K_f & -K_r+\frac{l_5}{l_4}K_c \\ -l_1K_r+l_3K_c+l_2K_f & l_1^2K_r+l_3^2K_c+l_2^2K_f & -\frac{l_3(l_4+l_5)}{l_4}K_c & -l_2K_f & l_1K_r+\frac{l_3l_5}{l_4}K_c \\ -\frac{l_4+l_5}{l_4}K_c & -\frac{l_3(l_4+l_5)}{l_4}K_c & \frac{(l_4+l_5)^2}{l_4^2}K_c & 0 & -\frac{(l_4l_5+l_5^2)}{l_4^2}K_c \\ -K_f & -l_2K_f & 0 & K_{tf}+K_f & 0 \\ -K_r+\frac{l_5}{l_4}K_c & l_1K_r+\frac{l_3l_5}{l_4}K_c & -\frac{(l_4l_5+l_5^2)}{l_4^2}K_c & 0 & K_r+\frac{l_5^2}{l_4^2}K_c+K_{tr} \end{bmatrix}$$

$$[K_r]=\begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ \omega^2 & 0 & 0 \\ 0 & K_{tf} & 0 \\ 0 & 0 & K_{tr} \end{bmatrix}$$

5.2 Simulation analyses

Inputting the actual and testing parameters, as well as the engine and random road excitations, into the model, the vibration is simulated.

Virtual vehicle runs on the virtual road (taking Wiener process as road surfaces signal) at the speed of 40km/h. Measuring the corresponding places in virtual and actual vehicle respectively, and then the vibration acceleration PSD of different places are obtained. (see Figure 7-12.)

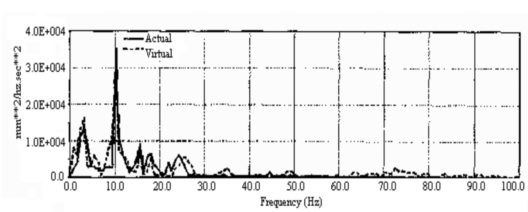

Figure 7. Vertical acceleration PSD (driver chair base)

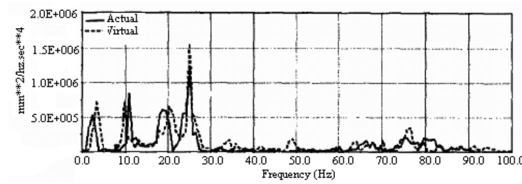

Figure 8. Vertical acceleration PSD (front axle gudgeon)

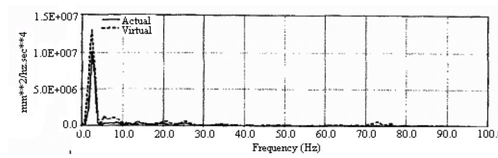

Figure 9. Vertical acceleration PSD (rear axle gudgeon)

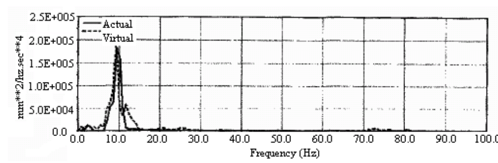

Figure 10. Vertical acceleration PSD (engine cylinder body)

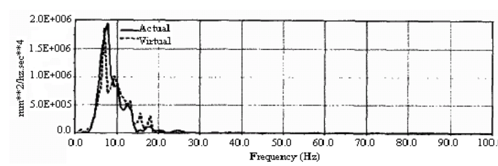

Figure 11. Vertical acceleration PSD (rear axle)

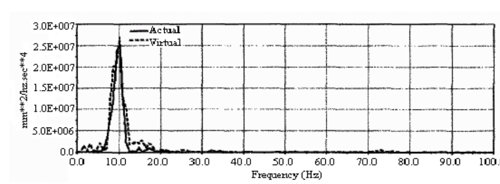

Figure 12. Vertical acceleration PSD (front axle)

Figure 7-12 shows that the Vertical acceleration PSD predicted using the virtual vehicle and road are in close agreement with that obtained using the actual vehicle and road at the corresponding places. It can be found that the main peak frequencies are approximately 10Hz, 25Hz, 3Hz, 9Hz, 7Hz, 10Hz (from Fig.7 to Fig.12). It should be noted that for a human being the most sensitive frequency range is 4-8 Hz. Thus, from a passenger ride comfort point of view, besides the excitation of rough road, the effects come from engine and driveline are not neglectable [9].

6 Conclusions

In this paper, the idea for the analyses of vehicle vibration based on Virtual Reality is presented, whose setup block diagram is given. Using the World Tool Kid (WTK), the virtual proving ground is established, as well as the virtual vehicle model by ADAMS software. Also, a conception on non-stationary random process power spectral density function (PSD) is presented and it is proved that the rough road PSD is non-stationary random process Wiener process PSD. For the purpose of the vehicle body vibration analyses with engine and random road excitations, a five- degree of freedom model is considered for half the vehicle and simulation analyses is performed by the help of the mechanical system simulation code ADAMS. Simulation results show that the Vertical acceleration PSD predicted using the virtual vehicle and road are in close agreement with that obtained using the actual vehicle and road at the corresponding places. By means of the established virtual environment, we can immerse into it and interact with the condition of virtual vehicle vibration. Thus, a rational and rapid evaluation on vehicle performance such as the ride comfort is attained.

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