Research Article

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Design and simulation of vehicle vibration test based on virtual reality technology

Abstract: When a car is operating, the road roughness will cause it to vibrate. When this vibration reaches a particular threshold, the driver will get uncomfortable and fatigued, affecting the bearing system’s durability and longevity. The vehicle vibration virtual test system’s framework design and implementation approach is based on virtual reality (VR), and it is made up of a VR subsystem, a model subsystem, and a virtual instrument subsystem. A virtual car vibration test system based on VR is built, and the results of the virtual vehicle vibration test are reported. The findings indicate that the virtual test (VT) technology theoretical model pertains to the creation of VT systems for car vibration based on VR. Users may monitor the vehicle vibration as well as its time domain and frequency domain signals in three separate observation modes using the system.

Keywords: virtual test system, vehicle vibration, virtual reality, virtual test

1 Introduction

Testing technology is an essential technology in modern industry. The development of computer technology promotes the birth and application of virtual testing (VT) technology. Virtual reality (VR) technology is another emerging technology in recent years; it has become an important force in the technological revolution in product manufacturing and assembly personnel training with its incomparable advantages. When these two technologies are combined, VR-based VT technology is born. Compared with the traditional test technology, it has a low cost, wide test range, and can carry out “predictive tests” before the product manufacturing and assembly, so it has gradually attracted the attention of the manufacturing circle and the academic circle.

VT is an essential component of the development process since it enables us to test more extensively. In everyday life, it is very difficult to encounter every imaginable circumstance. VT allow us to test several variants of the same scene in a controlled environment. VT is a simulation of a physical test that uses finite element analysis tools, multi-body dynamic analysis tools, and RPC iteration techniques to generate precise location and load motion, and damage parameters of a vehicle system particularly in the initial phase. This strategy has multiple benefits. VR is a high-level human–computer interface that can simulate the real environment and allow designers to interact with it. Its basic features are as follows: Immersion-Interaction-Imagination. Virtual testing technology refers to the simulation test research that can be carried out in the early development stage of a physical system through a software simulation method and “Virtual tests” such as performance and dynamic response characteristics of the system can be carried out through software simulation analysis [1]. VT highlights the importance of integration, engagement, and conceptualization in the system hence it plays a significant role. VR emphasizes that the system should have the characteristics of immersion, interaction, and conception; Virtual instrument (VI) focuses on the use of software for measurement, data analysis, real-time display, and storage. VT of vehicle
vibration based on VR and VI refers to the simulation of vehicle vibration by using VR technology, and the test information of vehicle vibration is displayed on the screen of the VI interface of the computer platform, to realize the VT of vehicle vibration. VT is the most often used nondestructive testing method. VT is a popular non-destructive testing (NDT) method since it is easy, affordable, and requires little equipment. The naked eye is used to inspect a component to discover whether there are any surface discontinuities. VT can be helped by optical instruments like magnifying glasses, boroscopes, mirrors, and other computer technologies for remote viewing. If a component can be seen, visual testing is the first approach used in an NDT examination [2,3].

When the vehicle is running, the road roughness will arouse the vibration of the vehicle. When this vibration reaches a certain degree, the occupant will feel uncomfortable and tired, which directly affects the ride comfort and ride comfort of the vehicle as well as the reliability and life of the bearing system. The fluctuation of the load between the wheels and the road surface also affects their adhesion effect, and the roughness of the road surface causes the driving resistance and vibration of the vehicle in the process of running. To improve the driving quality of vehicles, vehicle vibration has been studied from two aspects: road and vehicle. The traditional road research method is to select natural test sections or establish standard test sites according to experience. However, the selection of natural test sections is difficult to meet the standard of each grade of road surface, which is not conducive to the theoretical research. The standard test ground cannot completely replace the actual road conditions. At the same time, the traditional vehicle vibration research generally goes through several stages, such as vehicle conceptual design, detailed design, prototype production, test evaluation, and product release, but the prototype manufacturing needs to test, improve, and retest the prototype, which costs a lot of time and money. VR and VI technologies provide a feasible way for the research of vehicle vibration. In this study, a VT system of vehicle vibration based on VR is established, which provides a new method and approach for vehicle vibration research.

The Department of Computer Science at the University of North Carolina has used VR to research molecular modeling, aviation pilotage, surgical simulation, and building simulation. Dr. David Warner of Loma Linda University Medical Center and his research team have successfully used computer graphics and VR devices to explore problems related to neurological diseases. The Massachusetts Institute of Technology established the Media Lab in 1985 to conduct formal research on virtual environments [4]. The media lab has set up a test environment called Bolio to experiment with different graphical simulation techniques. Stanford research institute (SRI) Research has set up the Visual Perception Project to study the further development of existing VR technologies. After 1991, SRI carried out training research on military aircraft or vehicle driving using VR technology, trying to reduce aircraft accidents through simulation [5]. The Fraunhofer Institute for Computer Graphics in Darmstadt, Germany, has developed a VR combination tool called “Virtual Design” that allows images to be displayed in real-time alongside sound. Germany’s National Center for Mathematical and Computer Research (GMD) has set up a department to research Scientific Visualization and VR. Research topics include VR performance and conflict detection. Real-time volume view, image pair algorithm, echo, and software interface. The CAD Research Center of the North China University of Technology has completed two “863” projects in the field of VR research, including the automatic generation and synthesis software processing of stereo visual animation, the multimedia platform of VR image vehicle, and demonstration system and the related audio database, and the production of some related stereo-visual animation CDs.

The offered VR technique will assist in managing noise, vibration, and harshness, as well as optimizing vehicle performance and maintaining a comfort standard across their vehicle portfolio. This model has a direct impact on the vehicle’s ride comfort and driver’s ride comfort, as well as the bearing system’s durability and longevity. The VR subsystem and the VI subsystem are realized under the Windows2000 operating system by using Visual, and then the vehicle vibration virtual test system based on VR is realized. Through this system, the vehicle vibration under different road roughness excitations can be observed in three different observation modes, the time domain signal, wavelet domain signal, and Fourier frequency domain signal of vehicle vibration, the weighted vibration level of vehicle vibration and vibration evaluation can be observed simultaneously, and the results are in agreement with the expected results.

## 2 VT technology based on VR

### 2.1 Theoretical model of VT technology based on VR

Since the 1990s, the research on virtual manufacturing has been developing in both depth and breadth, which has accumulated a lot of experience for testing in the virtual environment and provided enlightenment, guidance, and help for the research of the topic [4].
Therefore, the VT system must be established from the beginning of the virtual design to make the product in the system, to select the material, and design the structure pertinent. When virtual machining of parts can be carried out in the corresponding VT system, cutting process simulation, special machining process simulation, manufacturing process simulation, and assembly simulation, and VT related to stress, deformation, heat, shape, size, and so on, to provide sufficient information for virtual machining of parts; and in aviation, aerospace, nuclear reaction, car crash test, has been widely used in the VR environment to carry out virtual machining of parts. The theoretical model of VT technology (Figure 1) consists of four interrelated layers: the perceptual layer, the functional layer, the information layer, and the physical layer.

1) **Perception layer:** the interface between the user and the VT system. The perception layer directly reflects the three basic characteristics of VR and highlights the difference between the VT technology based on VR and traditional testing means.

2) **Functional layer:** between the information layer and the perception layer, it is mainly composed of the testing model, simulation model, and training model, which directly reflect the purpose and significance of VT [5].

3) **Information layer:** the core part of the VT system, including all kinds of data, structures, algorithms, and programs that enable the VT system to work normally.

4) **Physical layer:** it is the physical foundation of the VT system, including the hardware environment, network equipment, test equipment, and software platforms that constitute the VT system. The theoretical model of VT technology based on VR provides a theoretical basis for the design of a virtual vehicle vibration testing system based on VR.

![Image](image_url)

**Figure 1:** Theoretical model of VT technology based on VR.

VRVT = VR ∩ CS ∩ TT.  \( (1) \)

In the formula, VRVT is a VR-based VT. VR – virtual reality; CS – computer simulation; TT-1 is the test technology.

Eq. (2) indicates that VRVT technology can be considered as the intersection of these three technologies. VR provides a visual representation and application environment for VRVT, and CS is VRVT.

### 2.2 Working principle of VRVT technology

Everything in the world changes with time, but the speed of change varies. Very slow changes, such as the evolution of a planet, are habitually treated as constant [6]. Things change for a reason. Both decision-making and prediction need to determine the relationship between the causes and effects of the things being made and predicted. Decision-making is to find the causes from the opposite direction of the results first, and then try to create conditions to achieve the results. Prediction is to predict the result from the cause, trying to find the cause to predict the result. The working principle of VRVT technology can be described as follows:

It will be obtained according to the experimental data. \( u(t) \) and \( a(t) \) are denoted by. (i) Remember on which the test is based, remember the model causality on which the test is based \( \tilde{F}(\cdot) \), and remember the test results in the working principle of the traditional test system and the hardware-in-the-loop VT system can be expressed as follows:

\[
Y(t) = \tilde{F}(\ddot{u}(t), \dot{a}(t)).
\]  \( (2) \)

According to the experimental data to obtain the required test results.

(ii) If \( u(t) \) and \( a(t) \) obtained according to the theoretical model are denoted as \( \ddot{u}(t) \) and \( \dot{a}(t) \), respectively, and are used to denote the model causality based on which the test is conducted if \( \tilde{Y}(\cdot) \) remembers the test results, the working principle of the VR-based fully VT system can be expressed as follows:

\[
\hat{Y}(t) = \tilde{F}(\ddot{u}(t), \dot{a}(t)).
\]  \( (3) \)

Therefore, let us say \( t > n \). \( u(t) \) and estimate the final output results of the test system. If \( f(t) \) does not change, \( Y(t) \) times \( t > n \). This is based on a theoretical model to predict the results of the output.
2.3 Framework of VR-based vehicle vibration virtual test system

According to the working principle of the vehicle vibration testing system, the framework of the vehicle vibration testing system based on VR is designed in this work by using the VT technology based on VR (Figure 2).

The vehicle vibration virtual test system based on VR is composed of a VR subsystem, model subsystem, and VI subsystem. The VR subsystem completes the visualization of the static road surface, trees, sky, lawn, mountains, and dynamic vehicles as well as the man–machine interaction of the system, so the vehicle vibration virtual test system based on VR has the perceptual property [7,8]. The model subsystem realizes the VT function of the vehicle vibration virtual test system based on VR by designing the road roughness model, the vehicle vibration physical model, the vehicle motion model, and the vehicle geometry model. The VI subsystem consists of the data layer, the processing layer, and the application layer. Through various data structures and algorithms, the information processing of the virtual vehicle vibration test system based on VR is realized [9]. The hardware and software required by the three subsystems constitute the physical foundation of the vehicle vibration virtual test system based on VR.

2.4 Implementation method of VR-based vehicle vibration virtual test system

1) The road roughness model of the model subsystem is used to generate different levels of road roughness data in line with the national standard GB7031-86 [10], and 3DS Max modeling software is used to design the geometric model of the vehicle.

2) In the Visual C++ environment, the road roughness data are visualized on the road surface by using the VR development software, and the geometric model of the vehicle and the trees, sky, lawn, and mountains are established by the VR development software loaded into the VR subsystem.

3) The road roughness data generated by the road roughness model will be input into the physical model of vehicle vibration, and the vibration signal of the vehicle will be output; the vibration signal of the vehicle is taken as the input of the vehicle motion model, and the vehicle pose output drives the vehicle to move in the VR subsystem.

4) The vehicle vibration signal output by the physical model of vehicle vibration is input into the data layer of the VI subsystem. After data processing by the processing layer, the time domain and frequency domain signals of vehicle vibration are displayed in the application layer in the form of a VI.

3 Experimental test analysis

Vehicle vibration refers to the vibration of the vehicle due to the action of road roughness in the process of vehicle running [11]. A vehicle vibration test is to make the tested vehicle vibrate by applying the required excitation and collecting the vibration response signal at the interesting part for processing and analysis, to provide a basis for the evaluation of the dynamic performance of the vehicle [12]. Excitation can be applied by driving the vehicle on the specified road or by generating the desired excitation signal through the excitation device on the test bench. In theory, to simulate the shape of the vehicle realistically, in addition to the same or similar geometric structure, geometric size, color, and texture of the actual system through geometric modeling, the vehicle vibration model
and motion model are also established to realize the simulation of the vehicle vibration [13]. When the car is operating, the road irregularity will cause it to vibrate. When this vibration reaches a particular degree, the driver may feel uneasy and exhausted, and it will have an impact on the bearing system’s dependability and longevity. The variation in load between the tires and the road surface impacts their adherence effect, and the irregularity of the road surface creates driving friction and shaking of the vehicle while it is running. Three subsystems are involved in the application of computer science; the establishment of the pavement roughness model involves information science, cognitive science, and pattern recognition theory [14]. Using statistical characteristics as indicators of vehicle vibration, Table 1 shows the relationship between vibration level and root mean square acceleration values and people’s subjective feelings.

When the vehicle is moving, the roughness of the road surface will arouse the vibration of the vehicle. When the vibration reaches a certain level, the occupant will feel uncomfortable and tired which affects the reliability and life of the bearing system. Due to the limitation of cognition and means, the road surface of the early test ground was copied according to the road roughness of the selected actual section, and the required road roughness data were obtained through repetition. With the development of computing technology, statistics, and other related disciplines, the method of using the statistical characteristics of the road surface to design the pavement irregularity through stochastic simulation has been increasingly applied [15]. Taking A-grade road surface as an example, the AR model and FD process model of discrete wavelet transform (DWT) were, respectively, used to simulate the roughness of A-grade road surface [16]. The FD process is a long memory dependency model that has gained popularity in recent years, owing mostly to its tractable mathematical features. Granger and Joyeux [17] and Hosking [18] suggested this technique first. Auto regressive modeling is employed as a model for recording the load performance while Finite Difference is a simulation technique to record the roughness of the road that has a direct impact on the vehicle’s ride comfort and occupant’s ride comfort, as well as the bearing system’s reliability and longevity. Figure 3 shows the result of A-grade road roughness simulated by the AR model. Figure 4 shows the results of class A pavement roughness simulation using the FD process model based on DWT.

When the vehicle is moving, the roughness of the road surface will arouse the vibration of the vehicle [19,20]. When the vibration reaches a certain level, the occupant will feel uncomfortable and tired which affects

| Root RMS value for acceleration | Vibration level | Human subjective perception |
|---------------------------------|----------------|---------------------------|
| <0.315                          | 110            | No comfort                |
| 0.314–0.62                      | 110–115        | Little uncomfortable      |
| 1.0–1.5                         | 114–123        | Discomfort                |
| 0.8–1.5                         | 118–128        | Quite uncomfortable       |
| 1.25–2.4                        | 112–126        | Very uncomfortable        |
| >2.0                            | 126            | Very uncomfortable        |

Figure 3: Results of A-grade pavement roughness simulated by AR model.

Figure 4: Simulation results of class A pavement roughness using the FD process model based on DWT.
the reliability and life of the bearing system. Due to the limitation of cognition and means, the road surface of the early test ground was copied according to the road roughness of the selected actual section, and the required road roughness data was obtained through repetition. With the development of computing technology, statistics, and other related disciplines, the method of using the statistical characteristics of the road surface to design the pavement irregularity through stochastic simulation has been increasingly applied [21]. Taking A-grade road surface as an example, the AR model and FD process model of DWT were, respectively, used to simulate the roughness of A-grade road surface [22].

According to the comparison between Figures 3 and 4, compared with the road roughness simulated by the AR model, the road roughness simulated by the FD process model based on DWT has a trend. In addition, DWT operation is needed in the identification of road roughness, and MODWT operation is needed in the mutation location of road roughness with mutation. Therefore, in this study, the FD process model based on DWT is used as the road roughness model in the VR-based vehicle vibration virtual test system. The simulation findings in the VR Environment indicate that substantial vibration isolation may be achieved under certain situations. The vehicle’s performance, particularly ride comfort and road holding capabilities, may be greatly enhanced. The findings of the VR simulation also reveal that the presented model outperforms the traditional methods. It has steadily caught the attention of the manufacturing circle and the academic circle because of its low cost, wide test range, and ability to conduct “predictive tests” prior to product manufacture and assembly, as compared to traditional test technologies.

4 Conclusion

The theoretical foundation of VRVT technology is applied to the VRVT system of vehicle vibration by naturally mixing VR and VI technology, and the system framework of VRVT system of vehicle vibration is developed. The system was divided into three subsystems: VR, model, and VI, and a virtual car vibration test based on VR was devised and executed. Pavement roughness, pavement roughness model, discrete wavelet transforms, maximum overlapping discrete wavelet transforms, organization of pavement roughness model in FD process based on DWT, recognition of pavement roughness FD process model, and simulation of pavement roughness with mutation were all investigated. The VT technology theoretical model based on VR is appropriate for the design of vehicle vibration virtual testing systems based on VR, which gives a novel technique to develop vehicle and machine tool vibration virtual testing systems. The virtual simulation of vehicle vibration and the VI display of vehicle vibration signal may be realized concurrently by the construction of a vehicle vibration virtual test system based on VR.

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