Applied Mathematics and Nonlinear Sciences

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Design and application of vibration performance testing system for commercial vehicles

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Submission Info

Communicated by Juan Luis García Guirao

Received November 27th 2020

Accepted January 31st 2021

Available online April 8th 2021

Abstract

The author presents the design and development of vibration performance detection and analysis system for commercial vehicles based on the theory of mechanical vibration performance testing and analysis theory, vibration signal acquisition and time domain analysis theory and Fourier transform principle.. The system performs the functions of data acquisition, signal analysis, spectrogram display, data storage, control output and time domain and frequency domain. Further, this system is used to test the vibration of commercial vehicles on the road to verify the integrity and reliability of the system function. The results of the experiments show that all functions of the system achieved the system design goals, and moreover, it shows that the system has strong practicability and high economy.

Keywords: system design and development, commercial vehicle, vibration testing, signal analysis

1 Introduction

Vibration is a ubiquitous natural phenomenon, and is an unavoidable movement phenomenon of motion producing dynamic loads. The machinery and engineering structures have to withstand and endure the dynamic loads [1]. Automobile vibration is an important factor affecting automobile performance. Vibration will have many effects on the various functions of automobiles such as smoothness, operation stability performance, ride comfort and service life of components and parts. In more severe cases, vibration will affect the speed of the automobile and increase noise simultaneously. Therefore, more and more automobile manufacturing enterprises begin to pay attention to the vibration performance detection of automobiles.

A series of dynamic signal acquisition and analysis software systems have been developed by scientific research institutes in domestic and overseas, such as modal analysis software developed by Danish B&K company

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MEscopeVES, Cada-X system by LMS company of Belgium, I-DEAS system by MTS company of USA, data acquisition software of Ni company of USA, DSPS dynamic signal acquisition and analysis system and MAS modal analysis software developed by RION company of Japan, DASP system of Beijing Dongfang Institute of vibration and noise technology, VAMS system of Nanjing University of Aeronautics and Astronautics, etc.

In recent times, it has become a hot spot of research topic in the automotive field and further how to carry out the vibration signal acquisition of the Automobiles, vibration testing analysis and scientific evaluation of the quality of vehicle operation effectively. Moreover, it has become a difficult research topic concerned with necessary measures to be taken, such as optimising mechanical structure and damping design, to reduce and suppress vehicle vibration.

2 Design of vibration performance testing system

2.1 Vibration data acquisition and signal analysis

The main task of vibration performance detection is obtaining the displacement, velocity, acceleration and other useful parameter information of the important parts of the motion machinery in the running state through sensors and display recorders. Vibration performance testing mainly includes vibration measuring device and signal analysis system. Vibration measurement measures the vibration responses or parameters such as displacement, velocity, acceleration and so on, of the relevant measurement parts in the state of mechanical motion, using various pressure sensors and vibration sensors and these sensors converts the input into the standard voltage or current signal output. The signal analysis system mainly consists of the function of vibration signal acquisition, display, processing and analysis and so on. It is the core of the system, which uses signal processing equipment and software analysis system to analyse and process the signals acquired by transmission, obtaining useful information, and evaluating the running condition scientifically and structural performance of motion machinery.

The signal can be divided into deterministic and stochastic, and most of the excitation forces generated by the automobile when in running state are periodic.

We can use common methods for signal time-frequency transformation with Fourier series and Fourier transform. According to Fourier transform formula, any complex periodic vibration can be decomposed into the sum of several simple harmonic oscillations. The whole motion state of simple harmonic vibration is determined by amplitude, frequency and phase. There will also be mixed noise signals in the collected vibration signals, which will affect the analysis results and cause signal distortion in severe cases. The common processing method is to amplify and filter the signal before collection, which eliminate the redundant vibration and noise signal. Then, the acquisition analysis is carried out to ensure the reliability and accuracy of signal analysis [2].

2.1.1 Signal acquisition

The core of signal acquisition is to continuously change the analogue signal, which is converted into standard time domain discrete digital signal through sampling, preserving quantization and coding and so on [3]. The signal sampling interval is divided into uniform sampling and non-uniform sampling. During sampling, frequency aliasing is found in the frequency domain.

According to Shannon's theorem, if the highest frequency of the signal is $f_{\max}$, in which frequency aliasing is not generated if the sampling frequency is more than 2 times, then it can be written as:

$$f_s > 2f_{\max} \quad (1)$$

In addition to satisfying Shannon's theorem, the sampling interval t and frequency f_s should also maintain the following relationship:

$$f_s = 1/\Delta t \quad (2)$$

After the sampling length N is determined, the sampling time T and frequency Δf resolution are calculated as

follows:

$$T = N\Delta t \quad (3)$$

$$\Delta f = f_s/N \quad (4)$$

According to Shannon's theorem, the sampling frequency is at least twice of the highest frequency of the signal. From the above equation, it can be seen that the shortest record length of the signal is:

$$T \geq N/2f_{max} \quad (5)$$

When the sampling length is fixed in the experiment, we must adopt a way of increasing the sampling frequency to avoid the phenomenon of frequency mixing [4]. However, it can be seen from the formula (3) that the higher the sampling frequency, the larger the frequency resolution Δf and the smaller the frequency accuracy.

In this sense, sampling frequency and frequency resolution actually constitute a pair of contradictions. Therefore, the solution is that the analogue signal is treated with anti-mixing filtering, that is, the analogue signal passes through a low-pass filter to remove the excess high-frequency signal and retain only the useful high-frequency signal to ensure that the signal analysis is accurate and not distorted.

2.1.2 Time-domain analysis

Time domain analysis is to analyse the stability, transient and steady performance of the control system according to the time domain expression of the output under a certain input.

Since time domain analysis is a direct method to analyse the system in time domain, it has the advantages of intuition and accuracy.

The determination of fatigue life structural design parts and the stability of working state of automobile are the hot and difficult points which are the concerns of automobile manufacturing enterprises.

It is necessary to analyse and estimate and establish load spectrum in all design process of automobile. Time domain analysis is an effective method to analyse various kinds of measurement random signals. The paper mainly expounds the calculation method of mean variance and mean square value in random state [5].

(1) Mean Value μ_x

$$\mu_x = \lim_{T \rightarrow \infty} \frac{1}{T} \int_0^T x(t) dt \quad (6)$$

(2) Variance σ_x^2 and Standard Deviation σ_x

$$\sigma_x^2 = \lim_{T \rightarrow \infty} \frac{1}{T} \int_0^T (x(t) - \mu_x)^2 dt \quad (7)$$

$$\sigma_x = \sqrt{\sigma_x^2} = \sqrt{\lim_{T \rightarrow \infty} \frac{1}{T} \int_0^T (x(t) - \mu_x)^2 dt} \quad (8)$$

(3) Mean Square Value ψ_x^2 and Effective Value ψ_x

$$\psi_x^2 = \lim_{N \rightarrow \infty} \frac{1}{N} \int_0^T x^2(t) dt \quad (9)$$

$$\psi_x = \sqrt{\psi_x^2} = \sqrt{\lim_{T \rightarrow \infty} \frac{1}{T} \int_0^T x^2(t) dt} \quad (10)$$

2.1.3 Fourier transform algorithm

Fourier transform can represent a function that satisfies certain conditions as a trigonometric function (sine function and/or cosine function), or linear combinations of their integrals [6]. The Fourier transform has a variety of variant forms in different research fields, such as continuous Fourier transform and the discrete Fourier transform. Fourier transform is a very important algorithm in the field of digital signal processing, which can be used to analyse the frequency components of periodic signals [7]. The periodic signal can be written as:

$$x(t) = x(t + nT) \quad (11)$$

In this expression (11), T is the period of the signal. If we intercept the signal arbitrarily, we can expand it into Eq. (12) as follows:

$$x(t) = a_0 + \sum_{k=1}^{\infty} (a_k \cos w_k t + b_k \sin w_k t) \quad (12)$$

In this expression (12):

$$a_0 = \frac{1}{T} \int_{-\frac{T}{2}}^{\frac{T}{2}} x(t) dt \quad (13)$$

$$a_k = \frac{T}{2} \int_{-\frac{T}{2}}^{\frac{T}{2}} x(t) \cos w_k t dt \quad (14)$$

$$b_k = \frac{2}{T} \int_{-\frac{T}{2}}^{\frac{T}{2}} x(t) \sin w_k t dt \quad (15)$$

$$w_k = k \frac{2\pi}{T} = k w_0 \quad (16)$$

Where w_k is the K circular frequency, $w_0 = \frac{2\pi}{T}$ is the fundamental frequency, and a_k and b_k are the K component of the Fourier series. Expressions 1.22 and 1.23 realise the transformation of the signal from time domain to frequency domain. The Fourier transform is divided into discrete Fourier transform (DFT) and fast Fourier transform (FFT). The comparison of the multiplication time of the two algorithms is as follows [8]:

$$\frac{FFT}{DFT} = \frac{\frac{N}{2} \log_2 N}{N^2} = \frac{\log_2 N}{2N} \quad (17)$$

If $N = 2048 = 2^{11}$, then $\frac{\log_2 N}{2N} = \frac{11}{2 \times 2048} = \frac{1}{372}$. It can be seen that the time used for FFT is 1/372 of DFT when $N = 2048$.

The calculation amount of discrete Fourier transform is greatly reduced by using the virtual, real and even properties of FFT, and it means – the larger the amount of data is, the more time is saved, and the speed increases by orders of magnitude. Therefore, fast Fourier transform is an algorithm that can greatly reduce the calculation amount and complete all points of calculation. As a result, it is decided to adopt fast Fourier transform during design calculation.

2.2 Design of vibration performance testing system

2.2.1 Design of the hardware of the system

The hardware part of the vibration performance detection system mainly includes vibration sensors, signal recuperator, signal acquisition instrument and signal processing instrument, as shown in Figure 1.

1) Vibration sensor: Vibration sensor is one of the key components in the measuring and testing technique, whose function is to receive the mechanical input and convert it into proportional electric output. As it is also an electromechanical conversion device, we call it as transducer, vibration pickup sometimes and so on [9].

Fig. 1 Hardware composition diagram of the system.

The vibration sensor does not change the original mechanical input to electric output directly, however, it takes the originally measured mechanical quantity of the parameter as the input of the vibration sensor. Then, it is received by the mechanical receiving part to form another mechanical quantity suitable for transformation. Finally, the movement of electrical and mechanical parts will convert the mechanical input into electrical output. Therefore, the working performance of a sensor is determined by the working performance of the mechanical receiving part and the electromechanical changing part. In this system, a piezoelectric type INV9821 acceleration sensor is used.

This system adopts the piezoelectric type INV9821 acceleration sensor which has integrated micro IC amplifier in it. The system integrates the traditional piezoelectric acceleration sensor and charge amplifier, which can be directly connected to the recording display and acquisition equipment, which make the test system simplified, with higher accuracy of measurement, and system performance more reliable. The INV9821 acceleration sensor has the frequency range of 0.5~5 KHz, the sensitivity of 50 mV/g, the ICP of 100 g, the weight of 25 g, the M5 installation thread, and the installation resonance frequency of 25kHz.

2) Signal conditioner: Signal conditioner is a kind of signal regulator between signal source and readout device, such as attenuator, preamplifier, charge amplifier and level conversion device, which is used for nonlinear compensation of sensor or amplifier [10].

The system adopts LC0201-5 signal conditioner, which can supply constant current directly to ICP piezoelectric accelerometer sensor to achieve signal gain. It can filter out the DC output through CR, which filter high frequency signals above 6KHz, and achieve anti-mixing filtering function, and use BNC connector to make the connection stronger.

3) Signal acquisition instrument: Signal acquisition instrument is a device that converts analogue electrical signals into digital signals and stores them for preprocessing. Further, a customer can see the captured data clearly in the wide colour screen of the acquisition instrument and set parameters to observe the waveform and data easily during the test. The captured data can be reproduced more easily and stored in the instrument memory or external USB memory. The signal acquisition instrument of this system adopts the domestic model of UA302S data acquisition instrument, which is connected to the computer through USB interface for digital-to-analogue conversion of signals. The product is equipped with 16-bit conversion chip, which can reduce quantization error and improve resolution.

4) Signal handling equipment: The signal handling equipment of this system adopts industrial notebook installed with Visual Studio 2015 development system. The signal handling equipment of the system adopts industrial notebook installed with visual studio 2015 development system. Visual Studio 2015 is a general purpose object-based programming language developed by Microsoft. It is a structured, modular, object-oriented, visual programming language with event-driven mechanisms that assist the development environment. The software part of vibration performance detection system is developed by visual studio 2015 development system, which can realise the functions of parameter setting, data acquisition, time domain waveform display, time domain refinement, frequency domain analysis, data storage, data reading, frequency domain filtering and statistical analysis.

2.2.2 System software development

This system software is developed based on Visual Studio 2015. The software of vibration performance detection system has the following functions: signal acquisition, data storage, data analysis, data reading, result display and data filtering. The overall software structure design is shown in Figure 2, and the flow chart of

system operation is shown in Figure 3.

Fig. 2 Software structure design.

Fig. 3 System operation flow chart.

The system transmits the vibration signal output by the sensor to the signal handling equipment (standard industrial CPCI chassis) for analysis. During the signal acquisition process, the analogue signal is input to the analogue-to-digital converter, which converts the input signal to the digital signal and transmit it to the computer through the USB interface.

In order to realise the functions above, the signal acquisition instrument has set up with a USB interface and provided with the standard driver and dynamic link library. After loading the driver, the system software can call the application program directly the interface function in the dynamic link library which realises the operation of the signal acquisition instrument [12].

The important interface functions of this system mainly include four functions: Open UA300, Close UA300, Minit and ReadData. The application of these four function systems is relatively mature which will not be described in detail.

2.2.3 Realisation of vibration performance detection system

Most of the existing vibration performance testing systems is intelligent testing instruments with microcomputer as the core. However, the cost performance is not high and the openness is poor, so it is not easy to expand the function. In addition, the intelligent test instrument is defined by the manufacturer and cannot be changed by the user. Also, its development and application lack flexibility.

Vibration performance testing system is composed of vibration sensor, signal conditioner, signal acquisition instrument, signal processing equipment and other hardware, which is combined with vibration performance testing software. The functions of acquisition, storage, display, analysis, refinement, filtering and statistical analysis of vibration signals can be realised through the graphical interface when the operator uses it. The hardware part of the system mainly realises signal input, filter and analogue-to-digital (AD); The system software realises data acquisition, data storage, time domain display, frequency domain analysis, data reading, frequency domain filtering and statistical analysis [13]. The composition of the test and analysis system and the signal

acquisition instrument are shown in Figure 4.

Fig. 4 Composition of test and analysis system and signal acquisition instrument.

3 Test application of vibration performance testing system

The main purpose of vibration test is to measure the vibration of the studied specimen by using modern testing methods. Then, the measured signals are analysed to obtain the mechanical vibration characteristics under various working conditions so as to provide reference for the structural design optimisation of the specimen.

3.1 Measuring point layout

The distribution of measuring points mainly follows four action principles, which are external force action point, important response point, cross-linking point of component or structure and mass concentration point. Taking the commercial vehicle as the test object, the vibration of different parts of the vehicle is measured under the condition – vehicle speed from 30 km/h to 100 km/h when driving on the expressway. There are 8 test points in the test arrangement, which are distributed in the front axle and rear axle of commercial vehicles, which is shown in Figure 5, and the specific location names are shown in Table 1.

Table 1 Test point installation location.

Point 1	Point 2	Point 3	Point 4	Point 5	Point 6	Point 7	Point 8
Vertical direction of first beam	Vertical direction of door frame	Vertical direction of engine	The front axle corresponds to the vertical direction of the frame	Vertical direction of transmission	Vertical direction of rear axle	Horizontal direction of rear axle (front and back)	The rear axle corresponds to the vertical direction of the frame

Fig. 5 Location of vibration test points.

3.2 Test procedure

3.2.1 Sensor installation

Acceleration sensor is installed with INV CZ-2 type magnetic seat. The sensor signal output is connected to the data acquisition card input port of INV3020D chassis through the measuring wire.

3.2.2 Measurement conditions

The measurement conditions are divided into 15 cases. The vehicle speed is from 30 Km/h to 100 Km/h, where the data is measured for every 5Km/h with the data measuring time of 60S. The test site is an asphalt expressway of the city and the test conditions are shown in Table 2.

Table 2 Vibration test conditions.

Test pavement	Condition 1	Condition 2	Condition 3	Condition 4	Condition 5	Condition 6	Condition 7	Condition 8
Asphalt road	30Km/h	35Km/h	40Km/h	45Km/h	50Km/h	55Km/h	60Km/h	65Km/h
Test pavement	Condition 9	Condition 10	Condition 11	Condition 12	Condition 13	Condition 14	Condition 15	
Asphalt Road	70Km/h	75Km/h	80Km/h	85Km/h	90Km/h	95Km/h	100Km/h	

3.3 Verification test and test data analysis

The experimental equipment is connected according to the experimental design, and the acceleration sensor signals are connected to the notebook through the 0 channel of the data acquisition instrument.

The signal generator generates a sinusoidal signal with amplitude of 5V, frequency of 500 Hz, and initial phase of 0, where the signal sampling frequency is set to 2000 Hz, and the length of collected data is 256. After the vibration signal is collected, the time domain waveform and frequency spectrum are drawn (as shown in Figures 8–11). Observing the waveform in the filter diagram, we can see that the filtered signal waveform is basically consistent with the original time-domain waveform. The experimental results prove that the collection, display, analysis, refinement, filtering and storage functions of this system can be well realised [14].

The change of vibration value of each measuring point under different working conditions was measured by the equipment, and the data were recorded and analysed statistically. The results of statistical analysis are instructive and show which speed is the safest and the most harmful when commercial vehicles are running. There are two types of statistical parameters: valid values and maximum values. Other parameters, such as minimum and maximum absolute values, can be selected according to the requirements of specific tests [15].

Fig. 6 Conversion curve of valid values at different speeds.

Fig. 7 Conversion curve of maximum at different speeds.

It can be seen from Figure 6 that the vibration of the 5th and 6th measuring points among the 8 measuring points is relatively large, while the vibration of other points is obviously smaller. With the increase of vehicle speed, the total effective value of vibration presents an increasing trend and reaches the maximum value at 95 Km/h. Therefore, it can be speculated that 95Km/h has the possibility for vehicle resonance. The specific causes of this phenomenon need to be further studied. It can be seen from Figure 7 that the change rule of the maximum value is different from the change rule of the effective value. The maximum value of the measuring point with a large effective value is not necessarily the largest among the 8 values.

The vibration test and analysis system can also obtain the vibration waveform and spectrum of each point at different speeds, as shown in Figures 8–11. The software can be used to analyse the frequency spectrum of vibration data under different working conditions, and the frequency composition of vibration under different working conditions can be obtained [16–18]. Therefore, the vibration analysis is the basis for structural design, improvement, vibration reduction and other measures [19, 20].

Fig. 8 Waveform and spectrum of each measuring point at a speed of 30 Km/h.

4 Summary

The vibration performance of automobile is directly related to the product's competitive advantage and customer's satisfaction, which is the most concerned point of automobile manufacturing enterprises.

Fig. 9 Waveform and spectrum of each measuring point at a speed of 60 Km/h.

Fig. 10 Waveform and spectrum of each measuring point at a speed of 80 Km/h.

Fig. 11 Waveform and spectrum of each measuring point at a speed of 100 Km/h.

Therefore, it is particularly important to develop the vibration performance detection system, which evaluates the vibration performance of the vehicle scientifically. It is particularly important for the system to take necessary vibration reduction measures to improve vehicle ride comfort, handling stability and service life.

Based on Visual Studio 2015 software platform, INV9821 acceleration sensor, standard industrial CPCII chassis and other hardware, this paper designs and develops a set of powerful friendly interface and reliable

commercial vehicle vibration performance detection system.

The vibration characteristics of commercial vehicles under different working conditions are effectively analysed through the test and verification experiment of the system during the continuous running process of commercial vehicles.

The final test data proves that the system has the characteristics of strong practicability, low cost, friendly interface, high reliability and so on, which can complete vibration test and analysis very well. The system has accurate measurement and perfect analysis, which fully meets the expected performance requirements. The system has a good application prospect in automobile manufacturing, rail transit, and engineering machinery, and in other fields that also has good marketing promotion.

Acknowledgement: This work was supported by the Academic Subsidy Project for Top-notch Academic Talents in Anhui Province(gxbjZD93) and the quality Engineering Project in Anhui Province (2019CXTD077).

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