Prediction of magnitude data of multi-channel vibration on a vehicle platform environment

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Abstract. The vibration prediction model of the key vibration source points of a vehicle platform is studied. Starting from the analysis of the factors affecting the vibration response and the correlation analysis, the key factors affecting the vibration response of the same vehicle structure are sorted out. The vibration prediction model of the key vibration source points is established by using neural network, and using the measured data to verify the accuracy of the vibration prediction model of the cabin section I, cabin II and cabin III of the platform. The results show that in the frequency range of 1~500Hz, the maximum error of root mean square of cabin I is 2.75dB, that of cabin II is 2.3dB, and that of cabin II is 2.97dB.

1. Introduction
At present, the hazards caused by vibration and noise during the operation of vehicle-mounted equipment are increasingly prominent, such as wire deformation and component lead breakage in the use of on-board electronic equipment, more than 50% of which are caused by vibration; more than 90% of structural strength failure of engine is caused by or related to vibration\cite{1-4}. It is one of the reasons for the lack of basic data in the design, finalization, assessment and verification stages of on-board equipment and the frequent occurrence of faults in the later stage that the technology of vehicle-mounted platform environment prediction is not mature and the prediction method is not systematic. Countries attach great importance to the research of platform environment prediction technology, especially the relationship between platform environment, platform type and task status. In 1992, the U.S. government launched the MERIT (integrated technology of task and environmental requirements) project, which applied the embedded algorithm (model) of task and environmental prediction and the knowledge of experts, from the task requirements and the prediction of life-span profiles to the environmental profiles of life-span formation, and finally obtained a real description of the dynamic process of environment, i.e. the magnitude and duration of environmental stress. In 1997, this technology has been a standard tool developed in the field of the United States, and has been incorporated into MIL-STD-810F “Environmental Engineering Considerations and Laboratory Test Methods”, and it has been applied in the development of many equipment. It can be more accurate than the standard to predict the induced environmental process of the platform, dynamically describe the environmental information of the platform, and provide a
basis for environmental design criteria, environmental test reduction, and environmental condition
determination[5]. From the mid-1980s to now, the relevant personnel of China have begun to make
some discussions and researches on the prediction of airborne equipment vibration environment by
referring to the methods of foreign countries, but basically they have not developed the computer
application system specially used for the prediction of airborne platform environment. In the 10th
and 11th 5-Year Plan periods, the airborne platform environment prediction system was initially
developed; the prediction system can establish a vibration environment prediction model based on
the measured data of the airborne platform environment, which provides tool support for the
development of environmental test conditions and reliability test profile of airborne equipment [6-8].
However, due to the lack of attention and limited investment in human, material and financial
resources, the development of vehicle platform prediction technology is slow. Based on a large
number of measured data in the early stage, on the assumption that the modeling vehicle and the
predicted vehicle have the same structural characteristics of the vehicle, this paper analyzes the
influencing factors and related lines of the vehicle platform vibration, determines the input
parameters of the model, establishes the prediction model of the vehicle platform vibration response
based on neural network, realizes the effective prediction of the root mean square of the key cabin,
and can provide technical support to the existing vehicle platform structure design and man-
machine-ring system engineering to a certain extent[9].

2. Analysis of factors influencing vibration response and their correlation

2.1. Analysis of the influence of road roughness on vehicle vibration and their correlation

Road spectrum is the power spectral density curve of road roughness, which is generally
characterized by its statistical characteristics[10-14]. In order to study the relationship between road
type and road spectrum, this paper collected the measured data of road surface elevation of 4 test
roads of two road surface types, in accordance with the relevant requirements of GB/T 7031-
2005 "Mechanical Vibration Road surface Measurement Data Report" standard[15], the road surface
spectrum is formed through analysis, and the octave center frequency of the road surface spectrum
is calculated, as shown in Table 1.

Table 1. Road surface spectrum characteristics of different types of roads.

| Road Type | Test road | Octave center frequency spectral density value (×10^6 m^2/m^1) |
|-----------|-----------|-------------------------------------------------------------|
| Type I    |           |                                                             |
| Type I-1  |           | 8.91E+01 3.35E+01 2.00E+01 2.00E+00 5.95E-01 2.16E-01 |
| Type I-2  |           | 4.02E+01 2.54E+01 1.01E+01 1.03E+00 2.25E-01 4.73E-02 |
| Type II   |           |                                                             |
| Type II-1 |           | 5.98E+03 1.63E+03 2.49E+02 3.35E+01 1.23E+01 1.87E+00 |
| Type II-2 |           | 3.11E+03 1.15E+03 2.34E+02 8.91E+01 3.89E+01 2.26E+00 |

According to the characteristics of road surface spectrum, according to GB/T 7031-2005
standard, the above roads are graded as shown in Table 2. It can be seen from Table 2 that the road
surface classification of road surface I is significantly higher than that of road surface II.

Table 2. Road surface classification of different types of roads.

| Road Type | Test road | Road class |
|-----------|-----------|------------|
|           |           | High frequency | Low frequency |
| Type I    | Type I-1  | Class B-C     | Class A-B     |
|          | Type I-2  | Class B       | Class B       |
In this paper, a total of 14 measuring points are selected, of which 8 were on X, Y, Z channels, 1 on channel X and Z, 1 on channel X and Y, 4 on channel Z.

To further analyze the correlation between road roughness and vibration acceleration, calculate the correlation between the two road roughness and the root mean square vibration of all measurement points. Figure 1 shows the scatter diagram of correlation coefficient between road roughness and vibration acceleration of all measuring points. It can be seen that only the correlation coefficients of root mean square vibration and road roughness of the X axis of the measuring point 4 and the Y axis of the measuring point 5 are lower than 0.8, indicating that the root mean square of vibration of most measuring points has a strong correlation with road roughness, and the root mean square of vibration increases with the increase of road roughness.

![Figure 1. Distribution of correlation coefficient of road roughness and vibration acceleration at all measuring points.](image)

2.2. Analysis of the influence of vehicle speed on vehicle vibration and their correlation

Analyzed from vibration principle, the speed directly determines the frequency at which the road excitation is applied to the vehicle, thus causing the vehicle vibration\textsuperscript{[16]}. Generally speaking, it will combine the speed with the road surface roughness, and transform the power spectral density to the time spectral density, thereby impacting vehicle speed and road surface on vehicle vibration is comprehensively characterized by the time spectral density. From the perspective of vibration energy, when driving on the same road conditions, the higher the vehicle speed, the greater the road excitation energy obtained by the vehicle in unit time, the more violent the vehicle vibration will be.

From the perspective of road surface spectrum, because the road surface power spectrum density regards the road section as composed of different short wave, medium wave and long wave, the road irregularity is analyzed the variance of elevation, speed and acceleration at different frequencies, and the road surface power spectrum density is expressed as:

\[
G_q(n) = G_q(n_0)(n/n_0)^{\omega}
\]

In the formula, \(n\) is the spatial frequency, representing the number of waves included in the length per meter, in m\(^{-1}\); \(n_0\) is the reference spatial frequency, \(n_0=0.1m^{-1}\); \(G_q(n_0)\) is the road power spectral density at the reference spatial frequency \(n_0\), representing the road roughness reference coefficient, whose value depends on the road surface grade, in m\(^2\)/m\(^{-1}\); \(\omega\) is the frequency index, representing the frequency structure of the spectral density.
Because the road excitation of vehicle vibration is density that characterizes road condition should be converted into time spectral density according to different vehicle speed. If the vehicle speed is $v$, the space frequency is $n$, and the time frequency is $f$, then:

$$f = nv$$  \hspace{1cm} (2)

$$G_g(n) = G_g(n_0)(f/(n_0v))^{-\alpha}$$  \hspace{1cm} (3)

The above analysis shows that when the Vehicle Speed $v$ increases, the spatial power spectral density increases accordingly, indicating that the frequency of road excitation increases, making the vehicle vibration more intense.

Calculate the power spectral density values of vibration data when a vehicle is driving at the speed of 40km/h, 50 km/h, 60km/h and 70km/h on the road surface I respectively. Figure 2 shows the comparison values of the power spectral density of vibration data in the vertical direction (Zaxis) of some samples such as 40km/h, 50km/h, 60km/h and 70km/h at the measurement point 1, point 5, point 6 and point 14, and the frequency bandwidth is [0,500Hz].

![Figure 1](image1)

(a) Point 2  \hspace{2cm} (b) Point 3.

(c) Point 10  \hspace{2cm} (d) Point 13

**Figure 1.** Comparative analysis of vibration power spectral density in Z axis at different speed on road surface I.

It can be seen from Figure 2 that with the increase of vehicle speed, the vibration value of four groups of measuring points in the low frequency band increases more obviously.

Figure 3 shows the distribution of the correlation coefficient between the vehicle speed and the vibration acceleration in X, Y and Z axes of all measuring points.
Figure 3. Distribution of correlation coefficient between travel speed and vibration acceleration at all measuring points.

It can be seen that only the correlation coefficient between the root mean square of vibration and vehicle speed in X axis of measuring point 5 and Y axis of measuring point 6 is lower than 0.85, which indicates that the root mean square of vibration and vehicle speed of most measuring points have a strong correlation, and the root mean square of vibration increases with the increase of vehicle speed.

Figure 4 shows the comparison values of the power spectral density of the vertical (Zaxis) vibration data of some test samples, such as measuring point 1, 2 and 4 when driving at 20km/h and 30km/h on road surface II, the frequency bandwidth is [0,500Hz].

Figure 4. Comparative analysis of vibration power spectral density at different speed on road surface II.
It can be seen from Figure 4 that with the increase of vehicle speed, except for the individual frequency at low frequency, the vibration power spectral density of four groups of measuring points increases with the increase of Vehicle Speed, which confirms the conclusion of formula (1).

3. Establishment and verification of vibration prediction model of vehicle platform

3.1. Basic modeling process
Based on the analysis of influencing factors of vehicle platform vibration and related lines, the input parameters of the model are determined. The factors related to vehicle platform vibration response include Vehicle Speed, road characteristics, tire characteristics, tire number, suspension characteristics, body structure parameters, etc. The modeling process of the vibration response prediction of the vehicle platform based on the neural network can be summarized as the following steps: first, the Vehicle Speed, road surface characteristics, tire characteristics, tire number, suspension characteristics and body structure parameters are taken as the input of the confidence network (DBN). Then, determine the initial parameters of the DBN model (such as the number of network layers, the number of neurons in each layer, learning rate and update direction, etc.) and the training parameters. The DBN model is established through iterative training until the optimal features are found, and the output is Characteristic parameters of influencing factors of vibration response of vehicle platform. The modeling process can be divided into two parts: model training and verification, and prediction with mature training model. In order to simplify the problem, the modeling vehicle and the predicted vehicle are assumed to have the same vehicle structure characteristics, that is, the same tire characteristics, tire number, suspension characteristics and body structure parameters. Therefore, only two types of parameters, Vehicle Speed and road surface characteristics need to be considered.

3.2. Model prediction process
For the established neural network model, the general expression is:

\[ B = F \left\{ (M_1, M_2, \ldots, M_i), (U_1, U_2, \ldots, U_j) \right\} \]

In the formula, \( M_i \) is the \( i \)th factor affecting vehicle vibration, \( U_j \) is the vibration response of the \( j \)th cabin, \( F \) is the mapping relationship between the influencing factors and the vibration response obtained by the deep neural network training, and expressed by the network structure parameter \( W \) obtained by the formula (4), which represents the vibration transmission characteristics of the vehicle platform, and \( B \) is a constant.

Input the data (vehicle travel speed, road roughness parameters and other characteristic values) of a cabin into the model of the established neural network, and the predicted value of the cabin's vibration response can be calculated.

3.3. Example of a vibration prediction model for a particular vehicle
The body of a certain type of vehicle includes of three sections: cabin section I, section II and section III, including 14 measuring points. The vehicle travels at different speeds on road surface I and road surface II respectively. The vibration prediction modeling, verification and prediction of the X, Y, Z axes of the three cabin sections are conducted respectively.

The road power spectral density values under different road conditions is smoothed, and the power spectral density corresponding to the center frequency of the road spectrum octave according to the center frequency of each frequency band calculated as recommended in Table 2 in GB/T 7031-2005. Considering that the input parameter dimension of the model should not be too large, the spectral density values corresponding to the sixth order spatial frequencies of 0.0625, 0.125, 0.25, 0.5, 1, 2 are selected as the input of the model. Table 3 illustrates the power spectral density values corresponding to the center frequency of the road spectral octave of a group of samples under two road types for modeling input.
Table 3. Center frequency spectral density value of path spectrum octave.

| Section name     | Sample No. | Road spectrum octave center frequency (x10^{-6} m^2/m^1) |
|------------------|------------|--------------------------------------------------------|
|                  |            | 0.0625      | 0.125        | 0.25 | 0.5 | 1 | 2 |
| Road surface I   | S-50-127   | 367         | 125          | 20   | 2   | 0.6 | 0.2 |
| Road surface II  | B-20-076   | 3642        | 1656         | 177  | 37  | 7.9 | 1.8 |

The roughness of different road surface types is also different. International standards ISO/DIS 8608[17] and GB/T 7031-2005 classify the road surface types into 8 categories. The logical numbers can be used to quantify the 8 road surface types. For example, the 8 road surface types are represented by the numbers 1-8 respectively as the input of the vibration prediction model. In this modeling process, there are two types of road surface: road surface I and road surface II, which are represented by logical numbers 1 and 3 respectively.

The vehicle speed is a continuous variable, and the acceleration response corresponding to the speed at every moment in the actual driving process is also different. Considering the needs of modeling input parameters, such as using single point speed as the model input, it will greatly increase the calculation amount, and it is difficult to accurately record the single point speed at each time in the actual measurement process. Therefore, it is recommended that the Vehicle Speed be divided into several sections, with the average speed of each section as the model input, and the section length can be adjusted according to the modeling needs. For example, the measured Vehicle Speed can be partitioned according to the interval length of 10km/h, and for the Vehicle Speed of (20, 30), 25 can be used as the model input.

In this modeling process, a vehicle traveling at the speed of 40km/h, 50km/h, 60km/h and 70km/h on road surface I, and the speed values in the corresponding model input parameters are 40, 50, 60 and 70 respectively. On road surface III, the speed is 20km/h and 30km/h respectively, and the corresponding model input parameters are 20 and 30 respectively.

There are usually dozens of measuring channels in each cabin. Perform self-power spectrum analysis on the time domain data of the vibration response of each channel to obtain the power spectrum data of the vibration response of different measurement points. Generally, the power spectral density can be calculated by Welch algorithm. Considering the large number of channels in each cabin, the upper limit of statistical induction of vibration response in each compartment or area can be used for model training. According to the data distribution characteristics of each cabin or area, the upper limit of normal tolerance or envelope method is selected to calculate the upper limit of the area as the vibration response characteristics of each cabin. For the obtained upper limit spectrum of each cabin, the power spectral density value in the concerned [0, 500Hz] bandwidth can be selected. After discretization, the value can be trained as the output of deep neural network.

In this modeling, 9 vibration prediction models in X, Y, Z axes of three cabins are established respectively. The modeling sample sources are in corresponding directions of each cabins at 20km/h and 30km/h of road surface I, 40km/h, 50km/h, 60km/h and 70km/h of road surface II, with the number of samples reaching more than 2400.

The neural network coefficient is set as shown in Table 4.

Table 4. Neural network coefficient.

| Network coefficient | Value       |
|---------------------|-------------|
| DBN network size    | [20 20]     |
| DBN training times  | 1000        |
| DBN random sample size per time | 10           |
| DBN update direction | 0           |
| DBN learning rate   | 1           |
Table 1: BP network training times

| Training Times | 100 |

Figure 5 shows the error convergence curve in X axis vibration prediction model of three compartments.

![Error Convergence Curves](image1)

(a) Cabin I model in X axis

(b) Cabin II model in X axis

(c) Cabin III model in X axis

Figure 5. Training error convergence curve of prediction model.

It can be seen from Figure 5 that with the increase of training times, the errors of the models all show a downward trend until they are less than the set threshold value, indicating that the model is established successfully.

9 groups of predicted models were validated with samples not involved in the modeling, and the number of validation samples is 6.

Calculate the actual and predicted root mean square of the vibration of the verification samples respectively, and calculate the error (dB) by formula (5), as follows:

\[ e = 20 \log \frac{RMS}{RMS_0} \]  

(5)

In the formula, RMS is the predicted root mean square, RMS\(_0\) is the measured root mean square, e is the prediction error.

For the vibration prediction model of cabin I in X axis, Figure 6 (a) gives a comparative analysis diagram of predicted spectrum and measured spectrum of a group of samples of cabin I in X axis when driving on road surface II at 70km/h. For the prediction model of vibration in direction II y, Figure 6 (b) gives a comparative analysis diagram of predicted spectrum and measured spectrum of a group of samples of cabin II in Y axis when driving on road surface I at 50km/h.
From the validation results of 9 groups of models, in the frequency range of 1~500Hz, the distribution trend of the actual value and the predicted value is basically the same, and the amplitude is relatively close, which proves that it is feasible to build the prediction model of vehicle platform environmental vibration by the deep neural network, and the maximum error of all validation samples of 9 groups of models is shown in Table 5.

**Table 5. Maximum error of predicted model.**

| Model No. | Vibration prediction model | Verification sample error |
|-----------|---------------------------|---------------------------|
| 1         | section I in X axis       | 2.10dB                    |
| 2         | section I in Y axis       | 2.75dB                    |
| 3         | section I in Z axis       | 2.41dB                    |
| 4         | section II in X axis      | 1.70dB                    |
| 5         | section II in Y axis      | 1.92dB                    |
| 6         | section II in Z axis      | 2.30dB                    |
| 7         | section III in X axis     | 2.97dB                    |
| 8         | section III in Y axis     | 2.37dB                    |
| 9         | section III in Z axis     | 2.54 dB                   |

It can be seen from Table 5 that within the frequency range of 1 to 500 Hz, the maximum error of RMS of cabin I is 2.75dB, that of cabin II is 2.3dB, and that of cabin III is 2.97dB.

Using the above prediction method and the corresponding cabin axial prediction model, the vibration power spectral density of a certain type of vehicle driving at 40km/h in the Z axis of cabin I, at 50km/h in the Z axis of the cabin II and at 60km/h in the Z axis of the cabin III are predicted. The predicted results are shown in Figure 7.
Figure 7. Results of vibration response prediction.

4. Conclusions

(1) Except for a few measuring points, the vibration root mean square of the most measuring points has a strong correlation with the road roughness, and the vibration root mean square increases with the increase of road roughness. At the same time, the root mean square of vibration has a strong correlation with the Vehicle Speed. The root mean square of vibration increases with the increase of the Vehicle Speed.

(2) The vibration prediction model of the key vibration source point is established by the neural network. The vehicle speed, road spectrum characteristics and road surface type are set as the input of the model, and the vibration response power spectrum density of the corresponding vibration point is set as the output. Different samples are trained and verified. The results show that the calculated vibration prediction value and the measured root mean square vibration value is ±3dB within the range of 1~500Hz.

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