Research on Modal Identification of High-Speed Maglev Guideway Structure Based on Data Fusion and Genetic Algorithm

JINGYU HUANG*, ZIYANG ZHANG, XIAONONG WANG and YUHAO ZHENG

ABSTRACT

High-speed maglev guideway structures are an important part of high-speed maglev transportation systems. A precise and efficient modal identification method for guideway structures is proposed to study the dynamic characteristics of high-speed maglev systems. Ensuring the safety of high-speed maglev transportation systems is of great significance. Taking the high-speed maglev guideway structure as the research object, this paper proposes a method for optimizing the sensor arrangement based on a genetic algorithm and a method for identifying the multi-order modes of the guideway structure based on data fusion. By optimizing the arrangement of the piezoelectric acceleration sensors and fiber Bragg grating sensors, data on the various dynamic characteristics of the high-speed maglev guideway structure under the excitation of high-speed maglev trains were obtained. The multimode characteristics of the high-speed maglev guideway structure were identified using the natural excitation technique and eigensystem realization algorithm through the fusion of multisource data of different types of dynamic characteristics in this study. The effectiveness of the proposed method is demonstrated by comparing the results of modal identification in different situations, for instance fusion of multi-source data. The research results indicate that the optimization of the arrangement scheme of sensors of high-speed maglev guideway structures based on genetic algorithm can effectively reduce the number of sensors

Jingyu Huang*, National Maglev Transportation Engineering R&D Center, Tongji University, No.4800, Caoan Road, Shanghai, China
Ziyang Zhang, College of Civil Engineering, Tongji University, No.1239, Siping Road, Shanghai, China
Xiaonong Wang, College of Transportation Engineering, Tongji University, No.4800, Caoan Road, Shanghai, China
Yuhao Zheng, Institute of Rail Transit, Tongji University, No.4800, Caoan Road, Shanghai, China

on the premise of ensuring the accuracy of modal identification results, and multi-source data fusion can significantly improve the accuracy of modal identification of the guideway structure, which proves the efficiency and accuracy of the methods proposed in this paper. The research results can provide effective methods for optimizing the sensor arrangement scheme for testing the dynamic characteristics and analyzing the dynamic characteristics of high-speed maglev guideway structures.

INTRODUCTION

High-speed Maglev transportation is a new direction for rail transportation development, and accurate identification of the guideway modal is important for the health monitoring of high-speed maglev systems. Common modal identification algorithms include the stochastic subspace identification method (SSI), random decrement method, natural excitation technique (NExT), time-series analysis technique, and eigensystem realization algorithm (ERA). The ERA is one of the most widely used algorithms for modal identification, with a small computational cost [1].

Li et al. used NExT-ERA to identify the modal parameters of the Tsing Ma Bridge [2], which proved the feasibility of this method for large bridges. Ye et al. used the stability diagram method to obtain the modal parameters of a cable-stayed bridge and eliminated spurious modals [3]. Dong et al. used the harmonic-modified random subspace method to identify the dynamic modal parameters of an offshore wind-turbine structure [4]. Guo et al. identified the modal parameters of suspension bridges based on data obtained from a health-monitoring system and investigated the relationship between the damping ratio and wind speed by calculating the modal damping of suspension bridges at different wind speeds [5]. Niu et al. used a hybrid method of complementary empirical modal decomposition and stochastic subtraction techniques using GNSS and real-time dynamic measurement data to identify the intrinsic frequency and damping of multi-span bridges with respect to their inherent frequencies and damping ratios. Most of the aforementioned studies only identified the frequencies and damping ratios of the structure without the modes [6]. Zhang and Huang used the NExT-ERA to identify the modal parameters and mode shapes of a maglev guideway [7]. However, the study was designed for sufficient sensors, which led to a higher testing cost. When performing structural health monitoring, it is usually desirable to obtain more modal data of the structure with fewer sensors. However, arranging fewer sensors can lead to difficulties in restoring the complete mode shapes. In this paper, a method is proposed to identify the modal parameters and mode shapes of a structure based on reconstructed response data, which can accurately obtain the modal parameters and mode shapes with fewer arranged sensors.

The purpose of this study is to accurately identify the modal state of a high-speed maglev guideway and to establish the basis for the structural health monitoring of high-speed maglev guideway system. Based on the parameters of the high-speed maglev guideway, a finite element (FE) model was established to obtain the modal matrix and eigenvalue matrix. Then, the Fisher information matrix of the guideway is obtained, and the key degrees of freedom (DOFs) of the relevant modalities are extracted using a genetic algorithm (GA) to maximize the fitness function and obtain the optimal sensor arrangement scheme. According to this scheme, a high-speed maglev guideway dynamic response field test was performed to obtain the acceleration and strain data using acceleration sensors and fiber Bragg grating (FGB) sensors. The excitation identification Kalman Filter (EIKF) method was used to fuse the data and reconstruct responses. Based on the reconstructed response, the NExT-ERA method is used to obtain the modal parameters and mode shapes of the guideway. The reliability of the method was verified by comparing the modal identification results based on raw and reconstructed data.

OPTIMIZATION AND MODAL IDENTIFICATION METHODS

In the field test, the number of sensors and their arrangement had a significant influence on the modal identification results. Typically, it is expected that a comprehensive and accurate structural parameter can be collected with as few sensors as possible under the influence of environmental noise, and the modal test results are robust and visible. However, in practice, as the number of sensors decreases, it becomes difficult to obtain the complete and accurate mode shapes of the structure. Although the sensors can collect the frequency signals of some mode shapes, it is difficult to reconstruct the complete mode shapes owing to the lack of test sites.

Optimization of Sensors Arrangement

Optimize the sensor arrangement based on the GA and effective independent effective independent (EI) algorithms. First, a group of individuals was generated to form the initial population, and the individuals were evaluated using the fitness function. The individuals are then crossed and mutated by genetic operators to generate a new population. Finally, the genes are selected by comparing the fitness values, so that genes with high fitness can be developed until finally converging on the optimal individuals. When optimizing the sensor position, individuals must be coded in the form of dualistic coding to accomplish crossover and mutation. The DOFs are selected through GA to maximize the two-norm of the Fisher information matrix, at which point the position corresponding to the set of DOFs is the best position for the sensor arrangement [8].

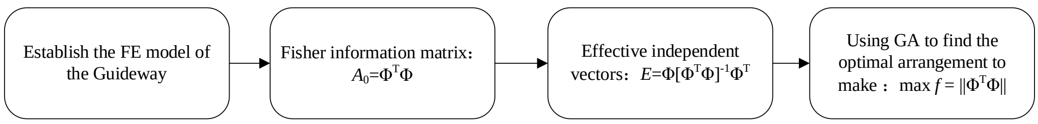


Figure 1. Sensor arrangement optimal process

Data Fusion and Response Reconstruction Based on Kalman Filtering

The Kalman filter uses a state-space model of a linear stochastic system consisting of state transfer and observation equations to describe the filter, and the effects of measurement and system errors are considered in the process. The recursive nature of the state equations is used to obtain the optimal estimates of the state variables with a minimum variance unbiased estimation criterion. The state vector of the system is derived based on the optimal estimation of the state variables of the system at each moment of the recursive process, and the structural response can be reconstructed from the state vector. When the excitation is unknown, an excitation identification Kalman filter (EIKF) can be used to estimate the external excitation and then reconstruct the structural response [9][10]. The EIKF process is as follows.

Eigensystem Realization Algorithm

ERA is a method that determines the minimum implementation of a system using test data. First, a Hankel matrix is constructed based on the test data. Then, a singular value is obtained by decomposing the Hankel matrix to determine the system matrix, control matrix, and output matrix. Finally, eigenvalue decomposition of the system matrix is performed to accomplish modal identification [10].

SENSOR ARRANGEMENT OPTIMIZATION AND IDENTIFICATION

Sensor Arrangement Optimization Based on GA

An FE model was established according to the parameters of the guideway, as shown in Figure 3. The modal and eigenvalue matrices of the guideway are obtained according to the FE model. Then, the Fisher information matrix is constructed by selecting the first 7th order modal of the structure, as follows:

$$A_0 = \Phi^T \Phi \tag{1}$$

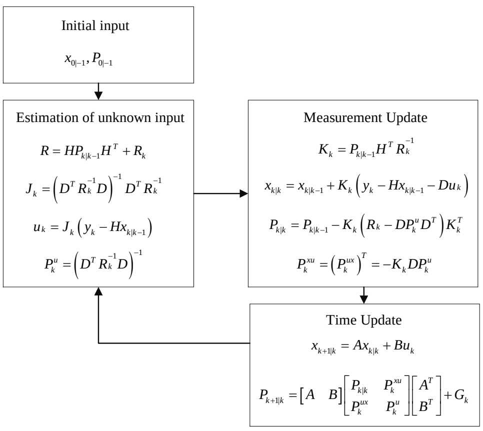


Figure 2. Process of EIKF

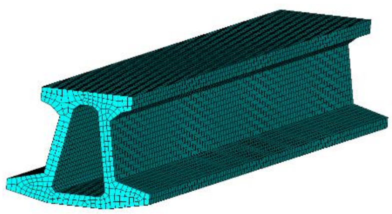


Figure 3. FE model of guideway

The number of sensors was set to seven, and the structural DOFs were selected by the GA.

$$\max\ f = \left\| \Phi^T \Phi \right\|_2 \tag{2}$$

The optimization process is illustrated in Figure 4. The optimal fitness of the population was achieved after approximately 30 iterations, and the optimal sensor arrangement is shown in Figure 5 and Figure 6. During the test, the FGB sensors were arranged at the corresponding positions of the acceleration sensors for the structural response reconstruction. A laser displacement sensor was added at the mid-span to verify the reconstructed response.

Data Fusion and Response Reconstruction

Figure 7.(a) shows the spanwise deflection of the structure calculated by the conjugate beam method based on the strain data. The displacement data obtained by this method are more complete with the low-frequency part, but the high-frequency noise is larger, which is not suitable for direct use in modal identification. Figure 7.(b) shows the midspan deflection obtained by secondary integration, which is not suitable for obtaining the midspan deflection because the results are significantly influenced by low-frequency noise. Figure 7.(c) shows

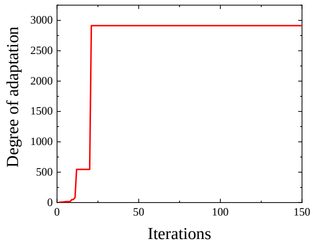


Figure 4. Variation of maximum fitness with iteration

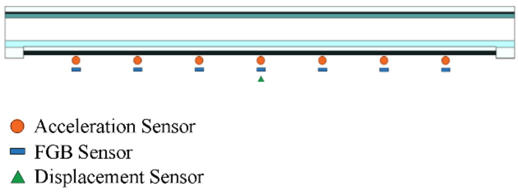
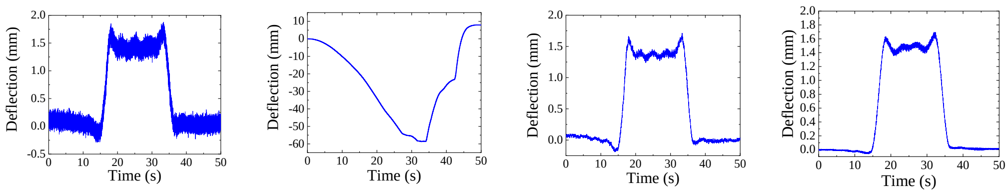


Figure 5. Sensor arrangement

Figure 6. Field test



(a) **(b)** **(c)** **(d)**

Figure 7. Mid-span deflection. (a) Based on strain data. (b) Based on acceleration data. (c) Based on reconstructed data. (d) measurement with laser displacement sensors

the mid-span deflection of the reconstructed response, which has a more reasonable displacement trend in the low-frequency part, and the signal retention in the high-frequency part is also more complete. The method can be used to obtain both the deflection and modal.

Comparing the mid-span deflection obtained by the reconstruction response and laser displacement sensor, the maximum value of the reconstruction response was 1.710 mm, and the maximum value of the laser displacement sensor was 1.696 mm. The difference is approximately 0.85%, which indicates that the response reconstruction has high accuracy.

According to Figure 8, it can be seen that the reconstructed response is more consistent with the laser displacement sensor in the frequency domain range than the other methods. Although the displacement based on the acceleration data has richer frequency domain components, it is more affected by noise interference, and the overall frequency domain amplitude is more distorted because it needs to obtain the displacement by secondary integration. Although the FGB sensor has a good low-frequency data acquisition performance, almost all the details of its signal in the high-frequency component are lost. A comparison with the laser displacement sensor shows that the reconstructed response signal is reliable in both the time and frequency domains, and can be used for modal identification.

Modal Identification Based on Reconstructed Response

Based on the EIKF, the response of the structure at 17 locations was reconstructed. With the reconstructed responses as the input, the NExT-ERA method was used to obtain the frequencies and mode shapes of the structure, as shown in Figure 8. Table I and Table II Comparing the modal identification results based on the reconstructed response and the raw data, it can be seen that there is no significant difference between the two methods in the natural frequency, and the error of the first four orders of natural frequency is less than 3.1%, which indicates that the method is accurate, and the modal frequency identification results based on the reconstructed response are reliable.

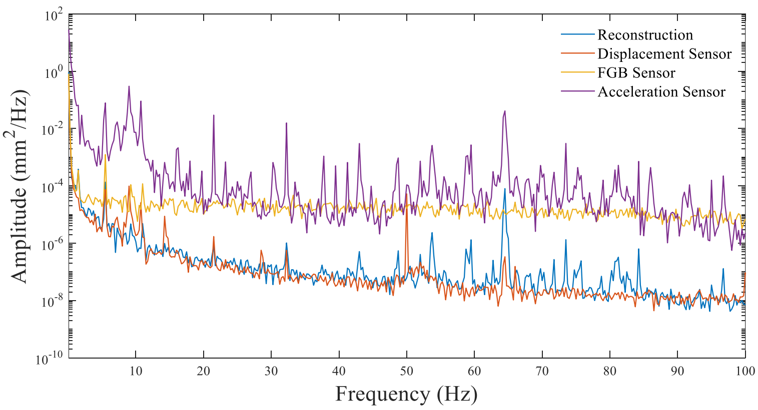
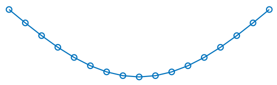
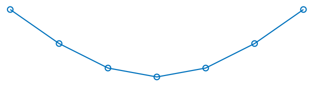
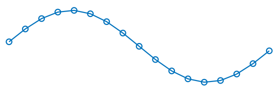
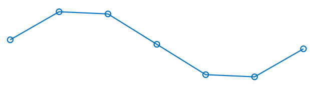
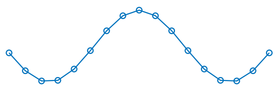
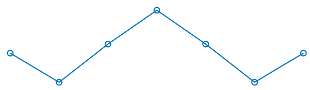
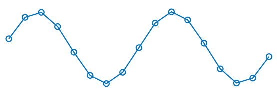
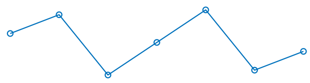


Figure 8. Frequency domain comparison of displacement signals generated by different sensors

TABLE I. COMPARISON OF FREQUENCIES BASED ON DIFFERENT DATA

Order of modes	Natural Frequencies (Hz)		Errors (%)
	Modes shapes based on reconstructed data	Modes shapes based on raw data	
First	9.52	9.58	-0.63
Second	38.07	37.60	1.25
Third	85.67	86.04	-0.43
Fourth	152.30	157.15	-3.09

TABLE II. COMPARISON OF MODE SHAPES ON DIFFERENT DATA

Order of modes	Modes shapes based on reconstructed data	Modes shapes based on raw data
First		
Second		
Third		
Fourth		

When modal identification is performed directly from the raw data, the results may not reflect the true mode shapes of the structure owing to the lack of test sites, and the key peak points may be missed in some mode shapes, resulting in distorted shapes, such as the 2nd and 4th order mode shapes in Table II. By reconstructing the response for modal identification, missing critical points can be avoided, and higher-order mode shapes can more accurately reflect the real vibration of the guideway.

CONCLUSIONS

In this study, the sensor arrangement was optimized based on the GA. The data fusion and response reconstruction of the acceleration sensors and FGB sensors were performed by EIKF. With the reconstructed response as input, the NExT-ERA method was used for modal identification to obtain the natural frequencies and mode shapes of the guideway. The conclusions are as follows. (1) The optimization of the sensor arrangement is carried out by the GA, which can obtain more accurate modal parameters when the sensors are limited. (2) Using EIKF to reconstruct the response of the structure, the peak deflection in the mid-span was 1.710 mm, which is only 0.85% different from that of the laser displacement sensor. The reconstructed data are consistent with the laser displacement sensor test results in the frequency domain. It is proven that the reconstructed data have high accuracy in both the time and frequency domains. (3) The modal identification results were compared based on the reconstructed and raw data. The difference between the first four orders of natural frequencies based on the reconstructed data and raw data was less than 3.1%. The 2nd and 4th order mode shapes are significantly better than the raw data, which proves that the modal parameter identification results obtained by the reconstructed response are reliable. The proposed method can be used to obtain more accurate mode shapes and improve the visibility of structural health monitoring.

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