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STUDY ON THE DYNAMIC RESPONSE CHARACTERISTICS OF TWO-SPAN CONTINUOUS GIRDERS IN HIGH-SPEED MAGLEV SYSTEMS

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Abstract

The guideway girders are the core load-bearing structures of the high-speed maglev transportation system. Their service condition directly affects the operational safety and stability of maglev trains. Monitoring the structural dynamic responses of guideway girders under normal operating conditions is of great importance for a comprehensive and reliable estimation of the system state. Accordingly, this study proposes a structural dynamic response monitoring method for two-span continuous guideway girders of high-speed maglev systems based on the field test and vehicle- guideway coupling dynamic simulation. First, a field test platform was established. The two-span continuous concrete girder and two-span continuous steel girder on the Shanghai demonstration line were selected as the research objects. Acceleration sensors were installed at the representative sections of the two girders. The test was conducted at a train speed of 300 km/h. Subsequently, the NExT-ERA method was applied for modal identification of the guideway girder, successfully identifying four mode shapes, which closely match the finite element results. Based on this, a vehicle-guideway coupling dynamic model of the high-speed maglev system was developed to perform numerical simulations of the guideway girder dynamic responses under various operating speeds. Combined with vehicle-guideway coupling dynamic simulations, the dynamic responses of the guideway girders under different operating speeds can be effectively evaluated. This work provides an effective technical approach for evaluating the service condition of high-speed maglev two-span continuous guideway girders.

Keywords: *High-Speed Maglev System; Two-Span Continuous Girder; Field Test; Dynamic Simulation*

1. Introduction

High-speed maglev transportation systems feature non-contact operation, high speeds, and small suspension gaps. The guideway girders directly bear the loads from the maglev trains. Therefore, their service condition directly affects the safety and stability of train operations. It also significantly impacts passenger comfort. Structural health monitoring (SHM) provides a reliable method to monitor and evaluate the dynamic characteristics of these girders.

Currently, many researchers have conducted studies on the dynamic characteristics of maglev guideway structures. Some scholars have developed vehicle-guideway coupling dynamic models to evaluate the dynamic evolution patterns of single-span girders [1]. Furthermore, various specialized sensors have been deployed in the field to achieve real-time monitoring of the girders' structural condition, including acceleration sensors [2], displacement sensors [3], and Fiber Bragg Grating (FBG) sensors [4].

However, existing studies have predominantly focused on the single-span girders of the Shanghai High-Speed Maglev Demonstration Line. During the development of the Shanghai Line, specific two-span continuous concrete and steel girders were designed. The dynamic responses of two-span continuous girders exhibit higher complexity compared to single-span units due to the structural continuity. Considering the widespread application of two-span continuous structures in track lines, targeted research on their dynamic characteristics becomes an essential engineering task

Therefore, this study proposes a SHM method for high-speed maglev double-span continuous girders, integrating field testing with vehicle-guideway coupling dynamic simulation. First, the low-order modes of the girders were successfully extracted from field test data using the NExT-ERA method, and the effectiveness of this identification was validated through a finite element model. On this basis, a vehicle-guideway coupling model was developed to investigate the dynamic response of the girders and the operational performance of the vehicle across a speed range of 150 km/h to 600 km/h.

2. Field Testing And Modal Identification

2.1. Monitoring Background and Setup

The field test was conducted on double-span continuous girders along the Shanghai high-speed maglev demonstration line. As shown in Fig. 1(a), both the concrete girder and the steel girder have a total length of 49.536 m. Functional components, each 3.096 m long, are installed along both sides of the girders. These components bear the levitation, propulsion, and guidance forces during train operation.

Ten vertical acceleration sensors and ten lateral acceleration sensors were installed on the bottom surface of each girder. They were placed at equal intervals of 4.128 m. Fig. 1(d) illustrates this specific layout scheme. Acceleration sensors (Model 941B, Fig. 1(c)) were deployed. The data sampling frequency was set to 3000 Hz. During the testing, the maglev train traveled across the girders at a speed of 300 km/h. The cross-section of the girder is illustrated in Fig. 1(e).

2.2. Modal Identification

Vibration acceleration data was collected during the high-speed passage of the maglev train at a speed of 300 km/h. The Natural Excitation Technique and Eigensystem Realization Algorithm (NExT-ERA) [5,6] method was then applied to extract the natural frequencies of the girders. First, the NExT method was employed to transform the structural responses under ambient excitation into cross-correlation functions, serving as substitutes for impulse response functions (IRFs). Specifically, sensors 1 and 3 were selected as reference channels to calculate the cross-correlation functions with other measurement points. Fig. 2(b) illustrates the cross-correlation function between sensors C3 and C1. Next, the ERA method constructs a state-space model of minimum order based on the IRFs of the system to extract the structural modal parameters. A Hankel matrix was constructed with 10,000 rows and 500 columns. Based on the singular value distribution plot (Fig. 2(c)), the truncation order was determined to be 360. The final identified modal parameters include the natural frequencies, damping ratios, and mode shapes.

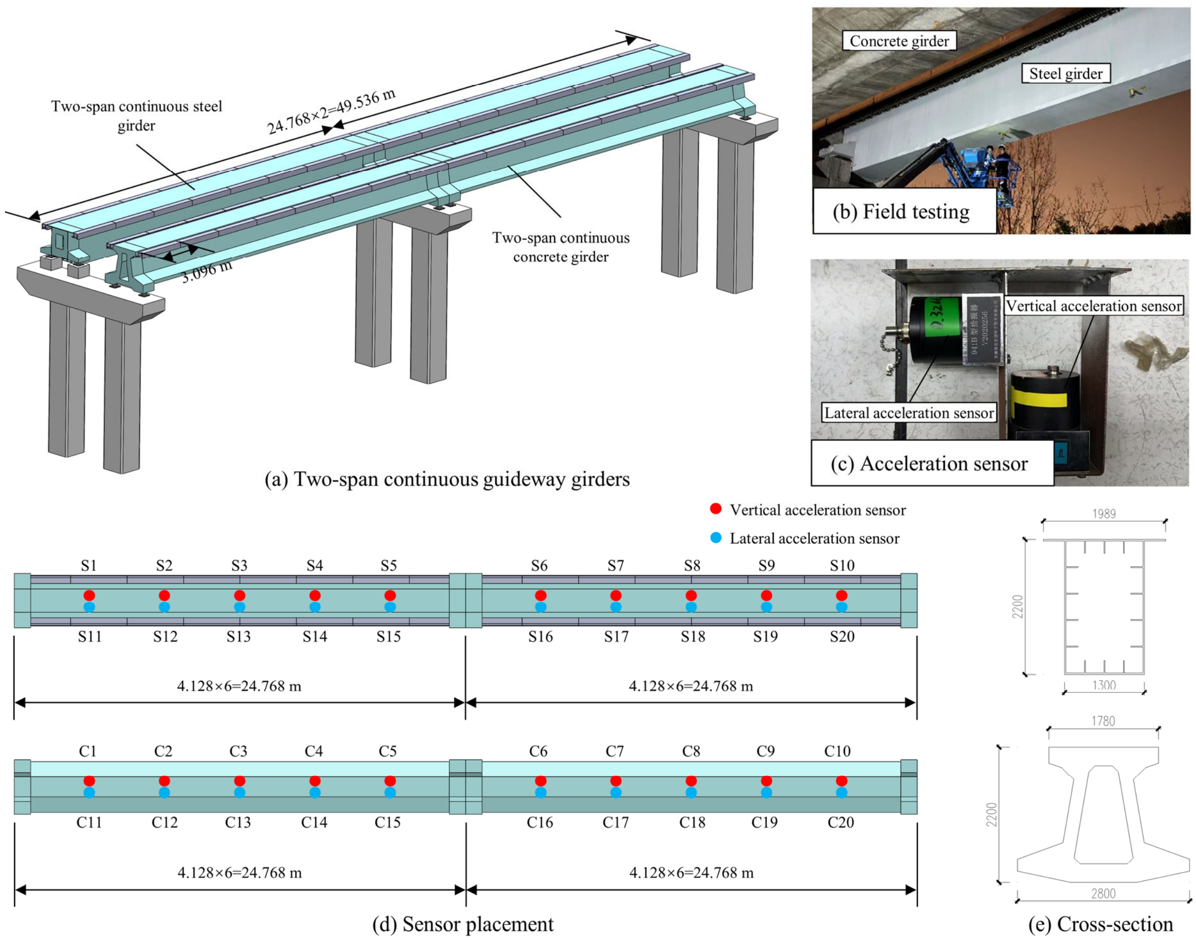


Fig. 1 – Field test platform

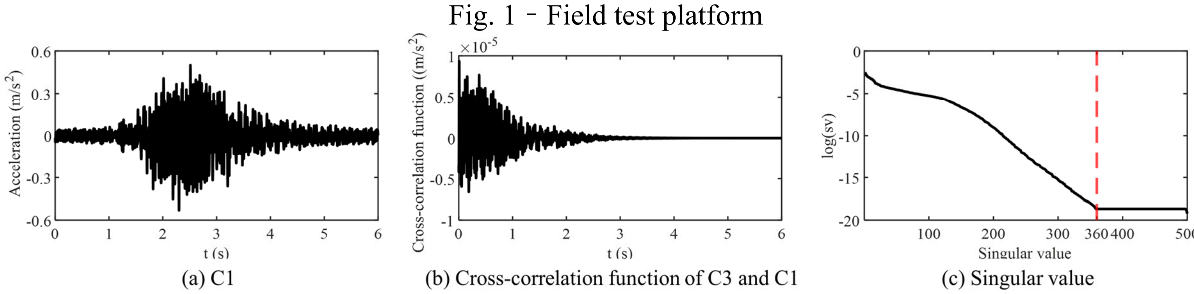
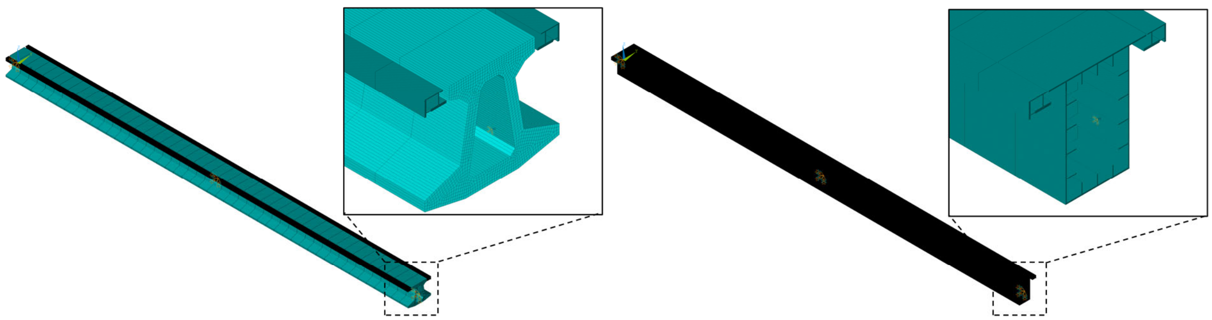


Fig. 2 – NExT-ERA method

2.3. Validation and Results

To validate the modal results identified by the NExT-ERA method, an ANSYS finite element model (FEM) was established. The model employs Timoshenko beam elements. The mesh and cross-section details are illustrated in Fig. 3. To simulate the connection between the functional components and the girders, the CERIG command was employed to achieve degree-of-freedom (DOF) coupling. The parameters for the finite element model are listed in Table 1. Notably, an additional mass of 383 kg/m was applied to the steel girder to account for the influence of diaphragms and secondary structures.



(a) Concrete girder (b) Steel girder

Fig. 3 – FEM

Table 1 – The parameters for the FEM

Parameter	Value
Elastic modulus of concrete	3.6×1010 N/m^2
Density of concrete	2500 kg/m^3
Poisson's ratio of concrete	0.2
Elastic modulus of steel	2.06×1011 N/m^2
Density of steel	7850 kg/m^3
Poisson's ratio of steel	0.3

The Consistent-Mode Indicator (CMI) was calculated to eliminate spurious modes [7,8]:

$$\mathrm{CMI}_i = \mathrm{EMAC}_i \cdot \mathrm{MPC}_i (\times 100\%) \tag{2-1}$$

Where EMAC_i is the Extended Modal Amplitude Coherence and MPC_i is the Modal Phase Collinearity. A higher CMI value indicates a higher probability that the identified mode is a true structural mode.

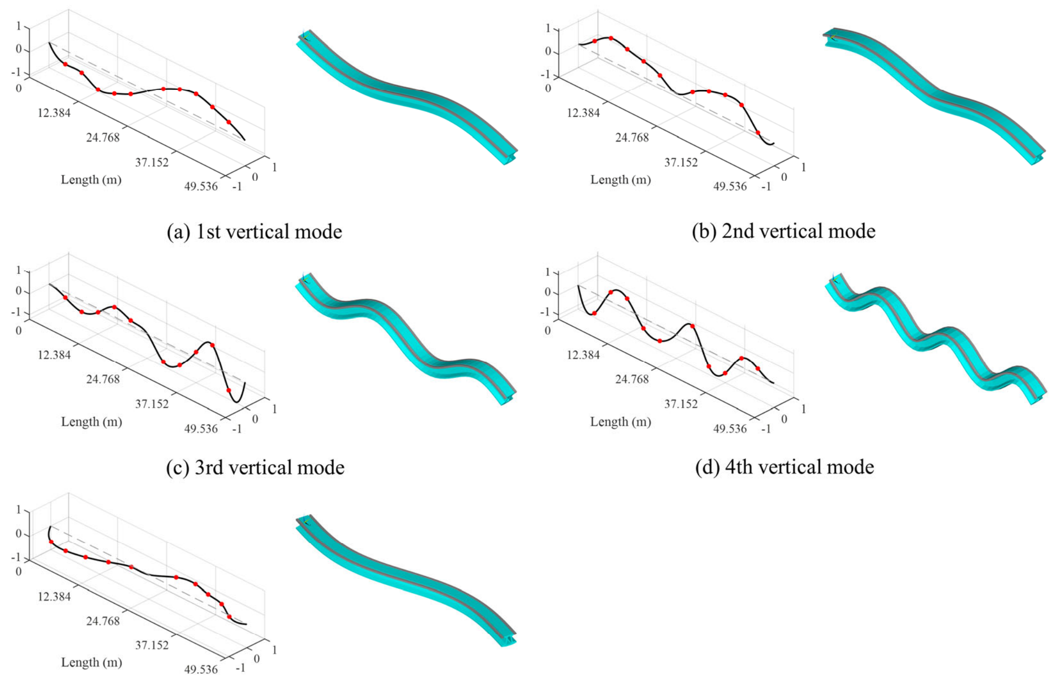
The identified modal parameters for the concrete girder are presented in Table 2 and Fig. 4, while those for the steel girder are shown in Table 3 and Fig. 5. The results demonstrate that the NExT-ERA method successfully identified the first four vertical modes and the first lateral mode of the concrete girder. Similarly, the first three vertical modes and the first lateral mode of the steel girders were also identified. The first-order vertical natural frequencies for the concrete and steel two-span continuous girders were found to be 7.7737 Hz and 8.9672 Hz, respectively. The natural frequencies identified by the NExT-ERA method are in good agreement with the FEM results, confirming the effectiveness and accuracy of the proposed method.

Table 2 – Modal parameter identification results for the concrete girder

Mode Order	Mode Type	FEM	NExT-ERA			Error
		Frequency (Hz)	Frequency (Hz)	Damping Ratios	CMI	
1st	Vertical	7.8153	7.7737	2.99%	98.31%	0.54%
2nd	Vertical	11.586	11.5742	3.77%	95.79%	0.10%
3rd	Vertical	28.4660	26.5642	0.43%	86.71%	7.16%
4th	Vertical	56.734	54.1832	0.46%	82.11%	4.71%
1st	Lateral	7.3577	7.7299	5.29%	83.04%	4.82%

Table 3 – Modal parameter identification results for the steel girder

Mode Order	Mode Type	FEM	NExT-ERA			Error
		Frequency (Hz)	Frequency (Hz)	Damping Ratios	CMI	
1st	Vertical	9.4368	8.9672	2.60%	97.86%	5.24%
2nd	Vertical	13.723	13.023	3.22%	94.13%	5.38%
3rd	Vertical	33.368	29.869	0.66%	97.56%	11.71%
1st	Lateral	8.6401	9.2951	1.63%	98.82%	7.05%

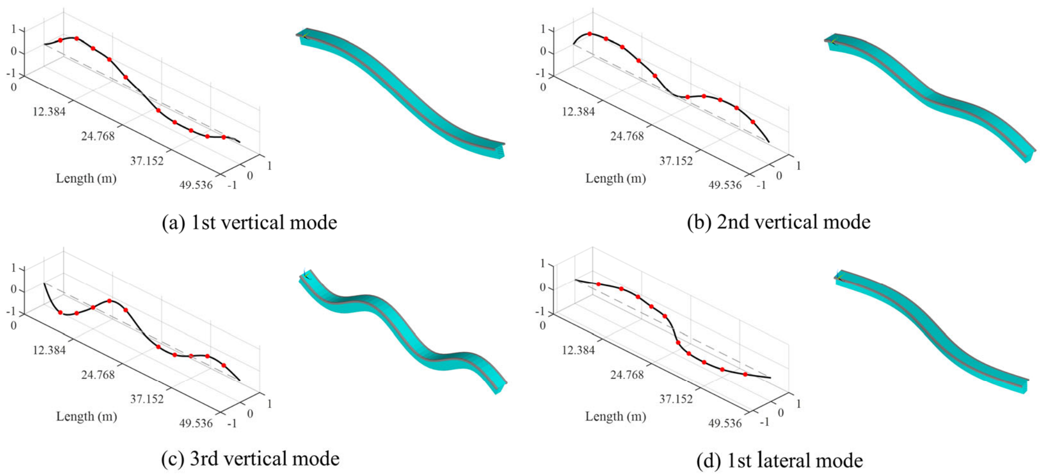


(a) 1st vertical mode (b) 2nd vertical mode

(c) 3rd vertical mode (d) 4th vertical mode

(e) 1st lateral mode

Fig. 4 – mode shapes for the concrete girder



(a) 1st vertical mode

(b) 2nd vertical mode

(c) 3rd vertical mode

(d) 1st lateral mode

Fig. 5 ‐ mode shapes for the steel girder

3. Vehicle-guideway Coupling Analysis

3.1. Establishment of Vehicle-Guideway Coupling Model

Based on the TR08 high-speed maglev train of the Shanghai Demonstration Line, a multi-body dynamics vehicle model was developed. Each vehicle consists of 101 degrees of freedom (DOFs), with a configuration of 5-car units. The girders are modeled as two-span continuous concrete and steel girders, with each span discretized into 100 Euler beam elements. The vehicle-guideway coupling model is illustrated in Fig. 6.

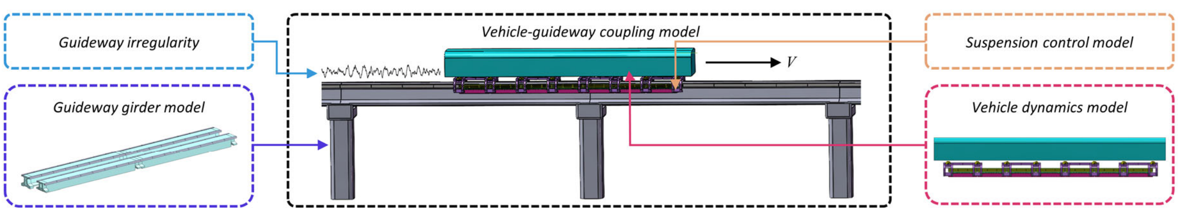


Fig. 6 ‐ Vehicle-guideway coupling model

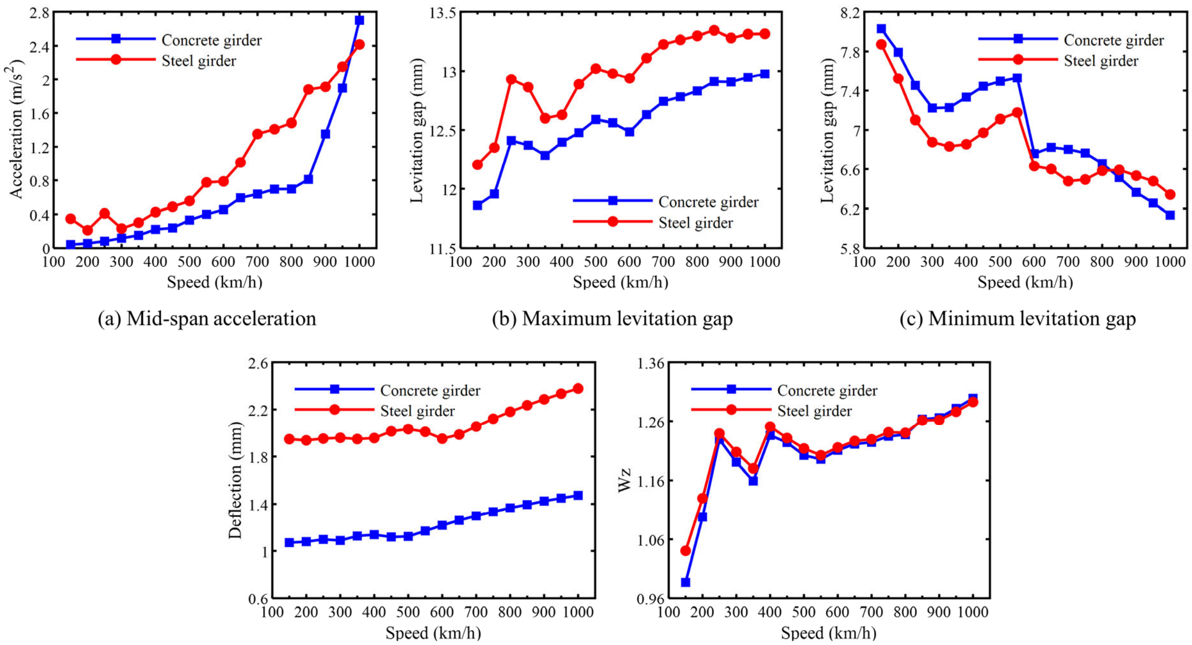
3.2. Simulation Results

Fig. 7(a) illustrates the mid-span acceleration of the girders at different speeds. The results indicate a positive correlation between vehicle speed and mid-span acceleration, with the steel girders exhibiting significantly higher acceleration levels compared to the concrete girders.

The maximum and minimum levitation gaps at different speeds are illustrated in Figs. 7(b) and 7(c), respectively. As the speed increases, the maximum levitation gap shows an upward trend, while the minimum gap follows a decreasing trajectory. This suggests that higher speeds amplify the fluctuations in the levitation gap; furthermore, these fluctuations are more pronounced when the vehicle traverses the steel girders than when it passes over the concrete girders.

Fig. 7(d) depicts the variation in mid-span deflection for the two-span continuous girders. Consistent with the acceleration trends, the mid-span deflection increases with speed. Notably, the mid-span deflection of the steel girder is considerably larger than that of the concrete girder.

Fig. 7(e) shows the Sperling index used to evaluate passenger comfort. The Sperling index for different girder types exhibit high consistency and increase as the speed rises. According to the Chinese code, Specification for dynamic performance assessment and testing verification of rolling stock (GB/T 5599–2019) [9], even when the high-speed maglev train reaches 600 km/h, the Sperling index remains below 2.5, achieving an "Excellent" rating.



(a) Mid-span acceleration (b) Maximum levitation gap (c) Minimum levitation gap

(d) Mid-span deflection (e) Sperling index

Fig. 7 - Simulation Results

4. Conclusion

This study proposes a dynamic response monitoring method for two-span continuous high-speed maglev girders, combining field testing with vehicle- guideway coupling dynamic simulation. The field test results accurately reflect the low-order modes of the two-span girders. When integrated with the vehicle- guideway coupling dynamic simulation, the proposed approach effectively evaluates the dynamic response patterns of the girders under various operating speeds. This study provides a reliable technical framework for assessing the in-service structural condition of high-speed maglev girders. The primary conclusions of this study are as follows:

1. The first-order vertical natural frequencies of the two-span continuous concrete and steel girders in the Shanghai High-Speed Maglev Demonstration Line are 7.7737 Hz and 8.9672 Hz, respectively. The natural frequency of the steel girder is slightly higher than that of the concrete girder.
2. Simulation results indicate that as travel speed increases, both the mid-span deflection of the guideway girders and the fluctuation amplitudes of the vehicle's levitation gaps exhibit an upward trend.

3. Simulation results indicate that the Sperling index exhibits a consistent upward trend as the train speed increases. At a speed of 600 km/h, the Sperling indices for the concrete and steel girders are 1.4914 and 1.4918, respectively.

Acknowledgements

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