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Research Article

Analysis and Control of Abnormal Vibration of End Wall on High-Speed Electric Multiple Units

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In view of the abnormal vibration of the body end wall during the high-speed operation of electric multiple units (referred hereafter as EMU), the vibration and noise characteristics of the body end wall area are analyzed through the line test. Combined with the end wall modal simulation results, the generation mechanism of the abnormal vibration of the body end wall is analyzed. The results show that when the train is running at a high speed, the aerodynamic excitation of the windshield cavity outside the body end wall acts on the end wall, arousing the first-order bending natural frequency of the body end wall, resulting in resonance of the body end wall, and then causing abnormal vibration and noise in the body end wall area. In order to solve this problem, installing a deflector (guiding plate) above the windshield in the vehicle body end wall area can effectively suppress the aerodynamic excitation acting on the vehicle body end wall. After optimization, the abnormal vibration and noise in the vehicle body end wall area are significantly reduced. The corresponding peak value at 40 Hz of the vehicle body end wall vibration spectrum is reduced by 85%, and the peak noise is reduced by 12%, The correctness of the mechanism analysis of abnormal vibration in the headwall area is verified, which provides a reference basis for guiding the structural optimization and operation and maintenance of rail vehicles.

1. Introduction

The rapid development of high-speed EMUs has brought rapid changes to people's travel. With the continuous improvement of the running speed of rail vehicles in the railway industry, the comfort of train rides has also become an issue of increasing concern [1–5]. The lightweight technology of the vehicle body is an important means to reduce operating energy consumption. However, excessive pursuit of lightweight structure often leads to insufficient stiffness of the car body and a decrease in the modal frequency of the car body [6–9]. When the vehicle runs at a high speed and the line conditions are poor, the elastic vibration of the vehicle body is intensified, resulting in obvious local vibration of the vehicle body, which greatly affects the ride comfort of the vehicle and even causes safety problems such as structural fatigue [10–15].

During the operation of high-speed trains, there are many external excitation sources and the stress on the vehicle system is extremely complex, causing strong vibration of the vehicle and its structural components [16–19]. At the same time, the rapid construction of railway vehicles has also made people put forward higher requirements for the structural design and comfort of trains. The lightweight design of vehicles has the advantages of reducing energy consumption, saving design costs, and increasing passenger capacity. It has gradually become the goal pursued by vehicle designers [20–25]. However, the lightweight design of the car body structure will cause insufficient stiffness in the car body, resulting in abnormal vibration of the vehicle during high-speed operation [26–30].

For a long time, the scholars have carried out a series of related studies on the vibration problems that occur during the operation of EMU. Gong et al. [31] took a certain type of high-speed EMU vehicle as the research object, combined the floor vibration test and simulation analysis, and explored the cause mechanism and control measures of the local floor resonance. Aiming at the problem of abnormal vibration of end wall structure, Xiao et al. [32] proposed a vibration reduction method for end walls based on particle damping technology, established a discrete element model of particle dampers on end walls, and arranged the dampers according to the energy consumption of the particle system. The scheme and the number of layers are optimized, and the acceleration response of the end wall under each vibration reduction scheme is analyzed through experiments. Aimed at the abnormal buffeting phenomenon of the car body in a certain type of high-speed EMU train, through the vibration test analysis and modal analysis of the car body and frame, Gong et al. [33] found that the serpentine motion frequency of the bogie caused by the lateral disturbance of the line was close to the diamond mode of the car body, which caused the abnormal buffeting of the car body. Based on the measured wheel tread and rail profile data, Liu [34] proposed two ways to improve the abnormal vibration of EMUs by studying the abnormal vibration of high-speed EMUs. Based on the vehicle-track coupling system dynamics model, Li et al. [35] analyzed that the resonance between the bogie's serpentine motion frequency and the first-order diamond modal frequency of the car body is the main reason for abnormal vibration.

Aiming at the abnormal vibration problem of the car body end wall in the high-speed operation of the EMU, this paper completes the analysis of the vibration and noise characteristics on the car body end wall region through the line test and analyzes the abnormal vibration generation mechanism on the car body end wall based on the modal simulation results of the end wall. The experiment verifies the optimized effect. The research in this paper can provide references and suggestions for the generation mechanism of abnormal vibration of EMU car body, structural optimization, and operation and maintenance of rail vehicles.

2. Abnormal Vibration Test of the Car Body End Wall

In the long-term tracking test of a certain type of EMU, the test data show that when the speed of the train is higher than 250 km/h, the vibration of the car body end wall area is large and serious abnormal noise is prone to occur. There are abnormal vibration phenomena that seriously affect the ride comfort and the smoothness of the vehicle's operation and may even cause fatigue failure of the vehicle's body structure. In order to effectively solve the problem of abnormal vibration at the end wall, it is urgent to accurately identify the source of abnormal vibration of the end wall of the car body. Therefore, under the high-speed operating condition of the EMU, a systematic vibration and noise test is carried out on the end wall of the car body.

In order to explore the abnormal vibration generation mechanism and abnormal vibration transmission characteristics on the car body end wall, determine the transmission path of the vibration source, according to the test methods stipulated by the ISO 2631 and ISO 3381 standards, and arrange sensors in the inner and outer sides of the end wall area on the car body, the floor, side walls, and other areas, respectively [36–38].

The test instrument uses a 12-channel real-time spectrum analyzer, and the sensors include four three-way vibration accelerometers, a microphone, and a surface microphone [39–41]. The above sensors are aggregated to the 12-channel real-time spectrum analyzer through cables to achieve the purpose of data synchronization. The specific models and parameters of the sensor are listed in Tables 1 and 2.

Figure 1 is a top view of the structure of the end wall area of the vehicle body. The inner side of the end wall of the vehicle body was the passenger compartment area, and the outer side of the end wall was the inner and outer windshield cavities. For on-site feedback, a surface microphone and an acceleration sensor were arranged on the outer surface of the car's body end wall, respectively. The accelerometer was 1.4 m away from the floor, and the noise measuring points were 0.7 m away from the floor. And, a microphone and an accelerometer were arranged on the inner side of the car body end wall, and the floor and side walls of the passenger compartment area were, respectively, arranged on the inner side of the car body end wall. The accelerometer was 1.0 m away from the floor, and the noise measuring points were 0.8 m away from the floor.

Figure 2 shows the vibration and noise measurement points of the microphone and accelerometer on the outer surface of the end wall. Figure 3 shows the local vibration measurement point diagram of the floor and side walls. The test process was divided into constant speed and acceleration conditions. Under constant speed conditions, the train operates at a speed of 300 km/h. During the test, the sampling frequency of the acquisition system was 16 kHz, the test time of each measurement point was not less than 20 s, and the acquisition test was performed not less than 3 times. For data with abnormal noise or vibration interference, the acquisition should be stopped immediately and eliminated. The single test time for this test was 2 days, with a total of 20 tests.

3. Analysis of Vibration and Noise Characteristics

3.1. Analysis of Vibration Characteristics. The vibration signals of each measuring point in the car body end wall, floor, side wall, and other areas are analyzed, and the narrow band spectrum of each vibration measuring point is calculated, as shown in Figure 4.

It can be seen from Figure 4 that when the train is running at high speed, the frequency-domain diagram of the vibration measuring points inside and outside the end wall of the car body has obvious peaks at the frequency of 40 Hz. The corresponding peak value at 40 Hz of the vibration spectrum outside the end wall of the car body is 1.6 m/s^2, and the corresponding peak value at 40 Hz of the vibration spectrum inside the end wall of the car body is 0.7 m/s^2.

It is found that the vibration spectrum of the measuring point in the floor and side wall area has no obvious peak near the frequency of 40 Hz, and the vibration amplitude is small,

Table 1: Main technical parameters of the microphone.

Parameter	Value
Sensor model	4189-A-021
Measuring range (dBA)	16~134
Output impedance (Ω)	<50
Frequency response (Hz)	1~20000
Sensitivity (mv·Pa^{-1})	40
Sound field type	Free field

Table 2: The main technical parameters of the accelerometer.

Parameter	Value
Sensor model	4354-B-1210
Measuring range (g)	50
Frequency response (Hz)	0.5~20000
Output impedance (Ω)	<100
A constant current source (VDC)	+12~+24
Working current (mA)	+2~+10
Sensitivity (mv·g^{-1})	100

indicating that the 40 Hz peak has nothing to do with the excitation under the bogie and the aerodynamic excitation outside the side wall from Figure 4.

Based on the above analysis, it can be seen that the abnormal vibration of the car body end wall is caused by the 40 Hz excitation of the car body end wall. This abnormal vibration is related to the excitation outside the end wall of the vehicle body and has nothing to do with the under-vehicle excitation of the bogie or the aerodynamic excitation outside the side wall.

3.2. Analysis of Noise Characteristics. In order to further confirm the correlation between the abnormal vibration of the car body end wall and the peak value of 40 Hz, a frequency spectrum analysis of the noise signals on the inner and outer sides of the car body end wall was carried out.

The spectrogram (one-third octave band) of the noise measuring points inside and outside the car body end wall is shown in Figure 5. It can be observed from the following:

(1) The spectrogram of the measuring points outside the end wall of the car body has peaks at 40 Hz and 80 Hz. When the train is running at high speed, the external excitation source is complex and there are many medium- and high-frequency components, so the outside noise measuring points have more medium- and high-frequency energy. The inner noise measurement point has a very obvious peak at 40 Hz, and the corresponding peak at 40 Hz is 66 dBA, which is 6–10 dBA higher than the noise value in other frequency bands.

(2) There is an obvious peak at 40 Hz at the noise measuring point inside the end wall of the car body. This law is consistent with the spectrum law of the vibration measuring point, which proves that the abnormal noise at the end wall is caused by the 40 Hz peak. The abnormal vibration is caused by the 40 Hz structural vibration of the end wall on the vehicle body.

4. Analysis of the Mechanism of Abnormal Vibration

4.1. Modal Analysis of the Car Body End Wall. As one of the important parts of the aluminum alloy car body on the high-speed train, the car body end wall is mainly composed of the skeleton, bent beam, and outer plate welding, the material is EN AW 6005A-T6, and shell element 181 is used to complete the mesh generation. During the calculation, the free modal of the car body end wall was calculated.

From the analysis results, it can be seen that the abnormal vibration is caused by the 40 Hz structural vibration. In order to further explore the cause of the 40 Hz structural vibration of the car body end wall, it is necessary to further analyze the mechanism of the abnormal vibration of the car body end wall at 40 Hz. In order to further explore whether the 40 Hz abnormal vibration of the car body end wall is related to the natural frequency, a finite element model of the car body end wall in line with the actual situation is established to analyze the mode of the car body end wall.

First, the finite element model of the car body end wall is established by using the shell 181 element in ANSYS software, the natural frequency and vibration mode of the car body end wall are calculated, and the correlation between the mode of the car body end wall and the 40 Hz structural vibration is analyzed.

Figure 6 shows the results of the finite element modal simulation calculation of the car body end wall. The first-order bending natural frequency is 41.7 Hz, and the mode shape is that the aluminum composite panels on both sides of the end wall are bent in the same direction.

According to the vibration characteristics of the end wall on the car body, it is concluded that the first-order bending natural frequency of the end wall on the car body is 41.7 Hz, which is consistent with the frequency of the abnormal vibration of 40 Hz. The abnormal vibration of the end wall area is the structural vibration generated by the first-order natural mode resonance of the end wall on the car body.

4.2. Analysis of Vibration Transfer Characteristics. According to the vibration and noise characteristics of the car body end area, the vibration and noise spectrum on the outside and inside of the car body end wall has obvious peaks near 40 Hz, indicating that the abnormal vibration excitation source at the car body end wall originates from the outside of the end wall. The modal simulation analysis results of the first-order bending natural frequency are consistent with the frequency corresponding to the peak value of the vibration and noise spectrum in the end wall area, and the abnormal vibration in the end wall area of the car body is generated by the bending resonance of the end wall.

It can be seen that when the train is running at high speed, the aerodynamic excitation of the windshield cavity outside the end wall of the car body acts on the end wall, which arouses the first-order bending natural frequency of the end wall of the car body, resulting in resonance of the end wall of the car body. This in turn causes abnormal vibration and noise in the end wall area of the vehicle body.

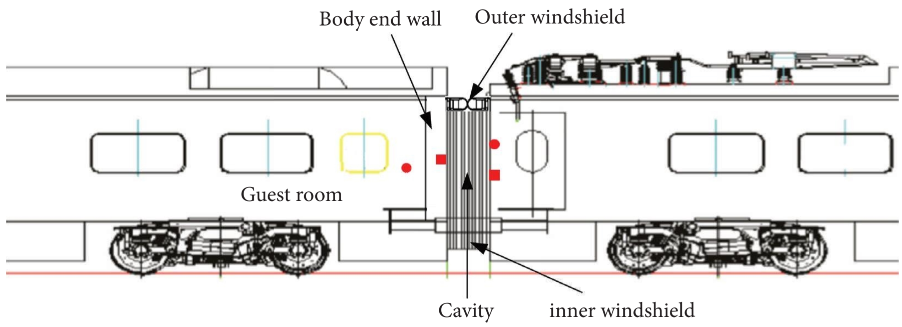

Figure 1: Schematic diagram of the layout of the car body end wall area (the circle represents the noise measuring point, and the square represents the vibration measuring point).

Figure 2: Vibration and noise measuring points outside the car's body end wall.

Figure 3: Local vibration measurement point diagram of floor and side wall.

5. Optimization Plan

The end wall of the train car body resonates due to external aerodynamic excitation, causing abnormal vibration and noise in the end wall area of the car body. The abnormal vibration is mainly controlled by the vibration source and the transmission path. Therefore, on the one hand, it can be controlled by weakening or eliminating the aerodynamic excitation source outside the end wall, and on the other hand, the first-order bending natural frequency of the car body end wall can be optimized and changed to avoid resonance of the car body end wall.

In view of the batch online commercial operation of trains, it is difficult to implement the method of optimizing the first-order natural frequency by improving the structure of the end wall of the car body and there are few measures

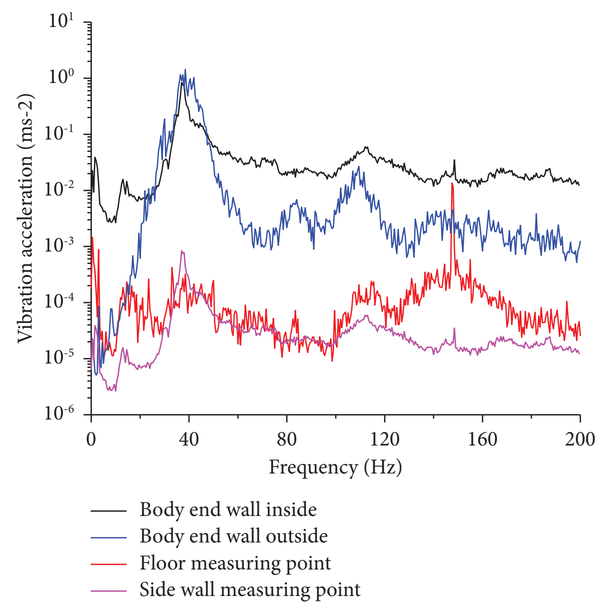

Figure 4: Vibration spectrum diagram of the inner and outer measuring points of the car body end wall, floor, and side wall.

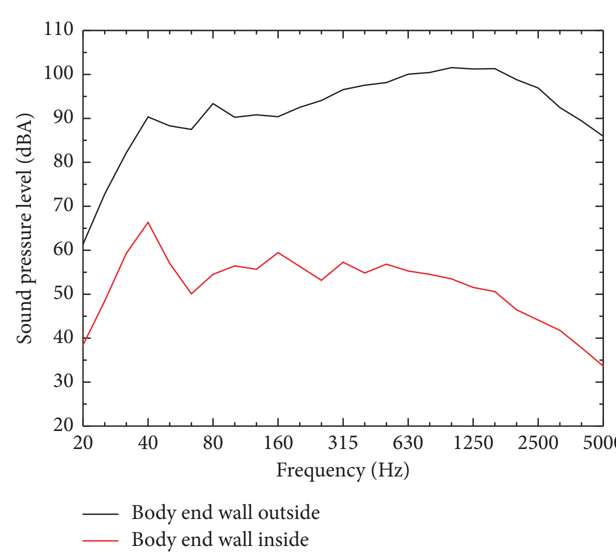

Figure 5: Spectrum diagram of noise measuring points inside and outside of the car body end wall.

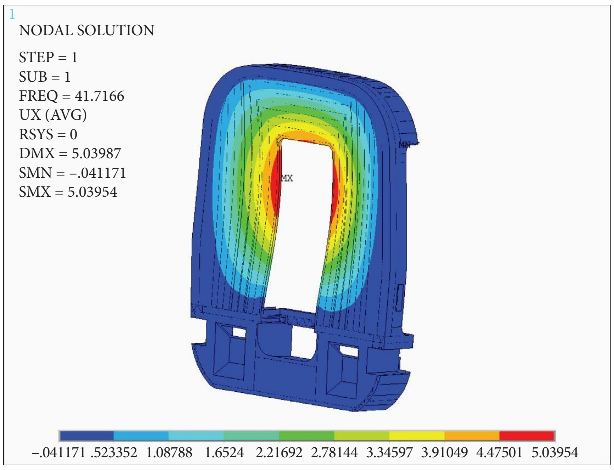

Figure 6: First-order natural frequency and mode shape of the car body end wall.

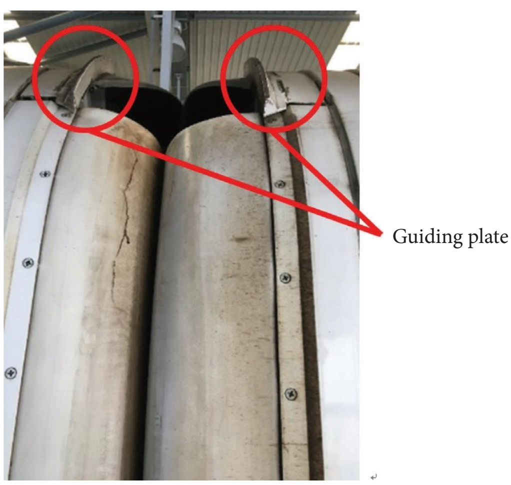

Figure 7: Specific scheme of car body end wall optimization.

that can be taken. Therefore, according to the structural layout of the end wall area of the car body and the windshield structure outside the end wall, this paper adopts the optimization measures of installing a deflector to guide the aerodynamic excitation outside the end wall of the car body to control abnormal vibration and the deflector is mainly used to reduce the aerodynamic load outside the body end wall. The specific implementation plan is shown in Figure 7. We install the guiding plate above the windshield cavity of the end wall of the train. Considering the wind resistance factor of high-speed train operation, the length of the deflector is designed to be short (20 cm). And the air deflector is a square aluminum profile that is fixed to the end wall of the car body of the EMU, including two transverse aluminum profiles (width is 20 cm) and one vertical aluminum profile (width is 5 cm). The aluminum profile and the end wall of the car body are rigidly fixed by bolts [1].

Figures 8 and 9 show the spectrum comparison results obtained from the vibration and noise tests on the inner side of the end wall area of the vehicle body before and after optimization.

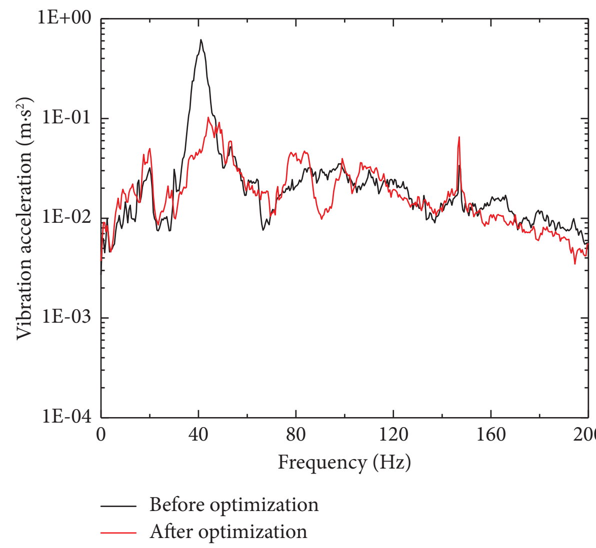

Figure 8: Comparison of the vibration spectrum of the inner side of the car body end wall before and after optimization.

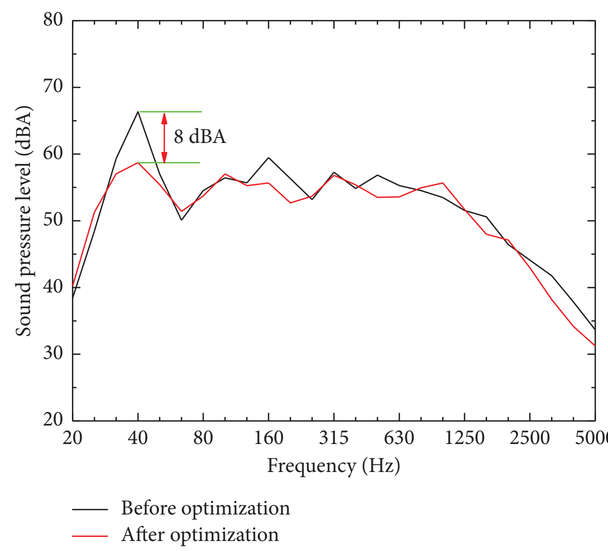

Figure 9: Comparison of noise spectrum on the inner side of the car body end wall before and after optimization.

Analysis of Figures 8 and 9 shows the following: (1) After installing the deflector above the windshield in the end wall area of the car body, the corresponding peak value of the vibration spectrum of the end wall of the car body at 40 Hz is significantly reduced, from 0.7 m/s^2 before optimization to 0.1 m/s^2, a decrease of 0.6 m/s^2. The reduction range reaches 85%, and the abnormal vibration of the end wall of the car body obviously reduces after optimization. (2) Comparing and analyzing the noise spectrum near the car body end wall area before and after optimization, the noise peak at 40 Hz is reduced from 66 dBA to 58 dBA, a decrease of about 8 dBA, and the reduction range reaches 12%. After optimization, the abnormal noise in the end wall area of the car body disappears. (3) By adding a deflector, the aerodynamic excitation acting on the end wall of the car body is effectively suppressed and the resonance phenomenon of the end wall of the car body is prevented. At the same time, the abnormal vibration and noise of the end wall area are obviously improved, and this also verifies the correctness of the analysis on the mechanism of abnormal vibration in the end wall area.

At the same time, according to Bernoulli's equation, the deflector can reduce the effect of aerodynamic excitation on the outside, thereby changing its natural frequency, avoiding the resonance phenomenon of the end wall of the car body, and significantly improving the abnormal vibration noise in the end wall area.

6. Conclusion

(1) During the high-speed operation of the train, the frequency-domain diagram of the vibration measuring points on the inner and outer sides of the end wall of the car body has an obvious peak at the frequency of 40 Hz. However, the frequency-domain diagram of the measuring points in the floor and side wall areas has no obvious peak near the frequency of 40 Hz, and the vibration amplitude is small. It is proved that the abnormal vibration of the car body end wall is caused by the 40 Hz excitation of the car body end wall and has nothing to do with the excitation under the bogie and the aerodynamic excitation outside the side wall.

(2) The first-order bending natural frequency of the car body end wall of 41.7 Hz is consistent with the abnormal vibration frequency of 40 Hz. The abnormal vibration of the end wall region is the structural vibration generated by the first-order natural modal resonance of the car body end wall. When the train is running at high speed, the aerodynamic excitation of the windshield cavity outside the end wall of the car body acts on the end wall, which arouses the first order bending natural frequency of the end wall of the car body, causing resonance of the end wall of the car body and then causing the car body to resonate. Unusual vibration noise is generated in the end wall area.

(3) In order to solve the problem of abnormal vibration of the car body end wall, after installing the deflector above the windshield in the car body end wall area, the corresponding peak value of the vibration spectrum of the car body end wall at 40 Hz is significantly reduced. After optimization, the abnormal vibration of the car body end wall obviously disappears. The method effectively suppresses the aerodynamic excitation acting on the end wall of the car body and prevents the resonance phenomenon of the end wall of the car body in the end wall area. It also verifies the correctness of the analysis on the mechanism of abnormal vibration in the end wall area.

(4) It is difficult to optimize the car body structure from the perspective of a long operation cycle, and it has also been solved from the perspective of commercial operation. The optimization method proposed in this paper is economical and practical and skillfully solves the problem of abnormal vibration of the end wall of a high-speed EMU.

Data Availability

The data used and/or analyzed during the current study are available from the corresponding author on reasonable request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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