Damping Property of Carbon Fiber Reinforced Plastic for Noise/Vibration/Harsh of Steering Column Support Assembly

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Title page

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ORIGINAL ARTICLE

Damping Property of Carbon Fiber Reinforced Plastic for Noise/Vibration/Harsh of Steering Column Support Assembly

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Abstract: Composite materials have penetrated into structural applications within the automotive industry, replacing traditional materials to reduce weight and then to improve fuel efficiency and to meet emission regulation. For some composite structural components, a significantly lower mode value compared to metal components can be accepted with an equivalent or better noise/vibration/harshness (NVH) performance, because, for composite materials, with different characteristics and much higher damping value compared to metal materials, a more sophisticated definition is required. An experimental investigation for mode definition of carbon fiber reinforced plastic (CFRP) steering column support assembly is discussed. Two kinds of composite steering column support assembly were manufactured, one is carbon fiber (CF) reinforced polyamide66 (PA66) with high mechanical properties, the other is glass fiber (GF) reinforced polyamide66 (PA66) with lower properties. The NVH test was carried out for these two components, and then the steering system mode requirement was defined by the test result. The new defined mode requirement obtained in the experiment showed good agreement with steering system mode analysis and test. By comparing the defined system mode requirement of composite component with that of the steel component, the effect of damping property of this composite material of the component can be clearly shown, which is over 21% percent on the NVH performance.

Keywords: Damping • CF reinforced PA66 • NVH • Steering column support assembly • GF reinforced PA66

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1 Introduction

The automotive industry is increasingly demanding for weight reduction as a result of demanding of new fuel-efficiency and emissions standards[1-2]. Composites can offer great deal of weight saving with respect to monolithic structural materials, and have been increased used by the automotive company in many vehicle parts such as door module, seat backs and spare-wheel well[3-9]. Recently, CFRP are a concern of the automotive industry and have become the predominant structural material, because of their high specific stiffness and strength. CFRP can provide much more weight reduction compared with other lightweight materials such as aluminum, high strength steel and GF reinforced plastics[10-14].

Construction of the automobile steering column support assembly is achieved which mainly includes the steering support cross tube, the steering column mounting bracket assembly, the left mounting bracket assembly, the right mounting bracket assembly and the central mounting bracket assembly. It is an important assembly part in the automobile, which provides the base architecture off which the steering column and IP components are attached and function. Due to the complexity of its design and its high performance requirement, the materials used for the production are metal, i.e. steel, magnesium, aluminum. Among these steel is most prevalent, but magnesium and aluminum are increasingly used due to the needs for weight reduction[15-16]. However, for steel and aluminum, the part integration is low and the production chain is long, there is tremendous need for component intensive. For magnesium, high degree integration can be achieved, but the cost of post treatment is high and then it is very hard to reduce cost[17]. Recently, composites especially CFRP are used to develop steering column support assembly to overcome the drawbacks of the metal component[18-20].

Regardless of its material of construction, the most demanding requirement for steering column support assembly is noise/vibration/harshness (NVH) test, because the steering column and various IP components are attached to it and function. The steering system mode was used to evaluate the NVH performance during the designing process. Due to the high damping of composite materials, the vibration attenuation of composite component is faster, and the forced vibration of composite component is lower at the resonance frequency[21-23]. Therefore, the mode requirement for composites steering column support assembly would be lower than that of metal component. However, it is very hard to test the damping value of the assembly[24-25], so we can't set the mode requirement based on the damping value. Then, we must find other easy method to affirm the mode requirement of composite steering column support assembly.

This paper describes the experimental method to set the steering system mode requirement for composite steering column support assembly of electrical vehicle (EV). One CAE model was used to analyze the steering system mode. Then two kinds of composite steering column support assembly were manufactured, and the NVH test was carried out. The steering system mode requirement was initially set according to the test result. The steering system mode test was conducted to verify the set mode requirement and CAE analysis result. Finally, the CAE model and the new set steering system mode were found appropriate for composite steering column support assembly of EV.

2 Methodology

For composite material, the damping value is much higher than that of steel, and the damping property would have much effect on NVH performance [26-32]. However, damping property is a reduction in the amplitude of an oscillation or vibration as a result of vibration energy being dissipated as other forms energy, including matrix damping, reinforced damping and material interface damping. Then, it is an important parameter for vibration control, noise reduction. Therefore, using high damping materials is an elegant way to reduce mechanical vibrations in mechanical engineering. Usually, the damping property of composite materials is much higher that of metal. Therefore, the stiffness of composite part can be lower that of the steel part, and the NVH performance requirement can be lower.

For steering column support assembly, the steering system mode is a crucial important parameter for NVH performance. Usually, the steering system mode would be defined before the steering column support assembly development so that the developed Steering column support assembly can satisfy NVH performance requirement. However, the damping property is extremely complex because of the different formation mechanism of its matrix damping, reinforced damping and material interface damping. Moreover, because of the complex shape of the composite component, the structural damping also plays an important role, the damping property is much more complex. So we can't evaluate the effect of damping property for the NVH performance of composite steering column support assembly directly for the reason that we can't test the damping property, and then the steering system mode requirement for composite steering column support assembly can't be defined.

Therefore, in this paper, an indirect method that is concurrent method (Figure 1) was used to study the effect of damping property for NVH performance of composite steering column support assembly. We can the reversed steps for this study. First of all, the steering system mode of the composite Steering column support assembly should be defined. Then, by comparing the defined steering system mode for the composite and steel component, the effect of damping property of composite material can be evaluated. The steering system mode was defined as follows, two kinds of composite components were manufactured: carbon fiber reinforced PA66 with good mechanical properties that can satisfy the NVH performance requirement and GF reinforced PA66 with much lower mechanical properties that can 't satisfy the requirement. Then, the NVH tests were concurrently conducted for the two kinds steering column support assembly. The steering system mode requirement of the composite component was defined by the vehicle dynamic testing of NVH tests for GF reinforced composite component, and was verified by the steering system test and vehicle dynamic testing of NVH tests of carbon fiber reinforced composite component. Finally, we can get the effect of damping property of the composite material on NVH performance of the composite steering column support assembly.

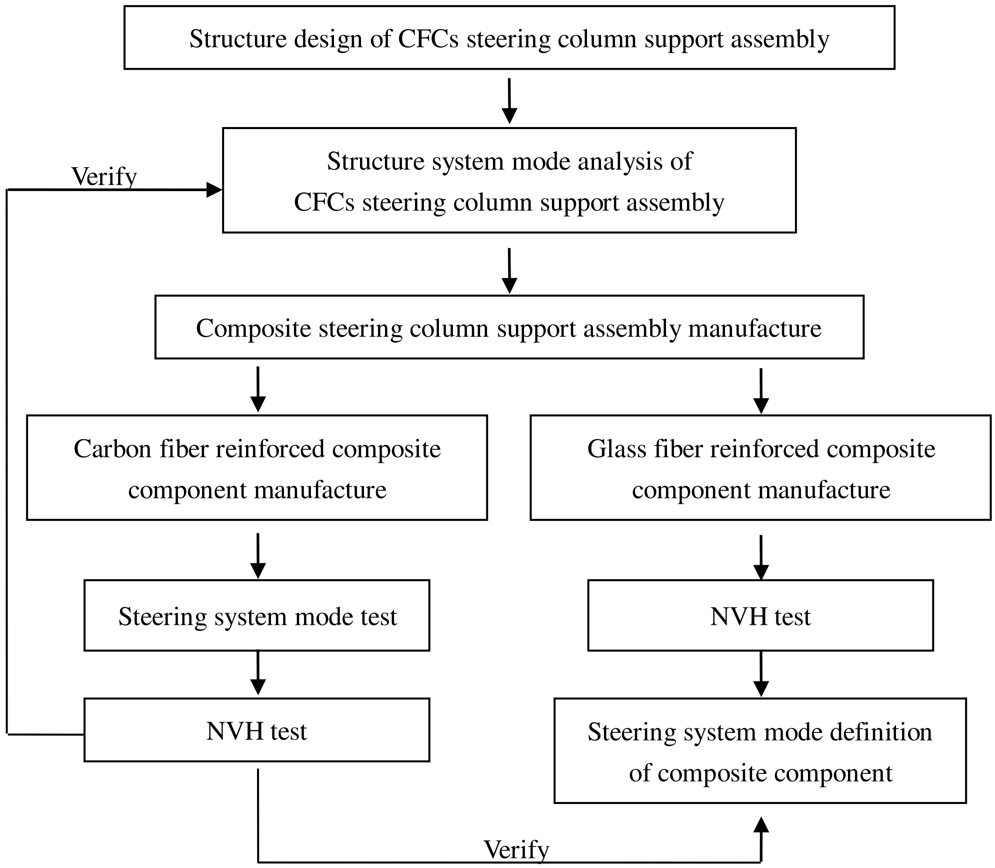


Figure 1. The concurrent test approach for composite Steering column support assembly

3 Steering system mode analysis

The detailed structure of composite steering column support assembly (Figure 2) was integrated into two parts: the steering column bracket assembly (the thickness is 4mm) and Steering column support assembly body (the thickness is 3.5mm).

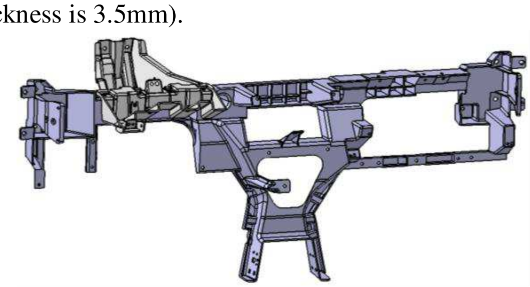


Figure 2. The detailed structure of the composite steering column support assembly

Because of the anisotropic material property of injection molding carbon fiber reinforced PA66 Steering column support assembly, the analysis method of steering mode analysis for this composite Steering column support assembly is definitely different from that of traditional metal Steering column support assembly. The used analysis method of the composite steering column support assembly is combined simulation. There are three steps for this method. The detail analysis process is as follows:

First of all, the carbon fiber direction of this composite part should be defined. Because carbon fiber flows along different directions during the moulding process of this composite part, the carbon fiber direction must be defined prior to the definition of material property. By mold flow analysis, the carbon fiber direction is defined as figure 3.

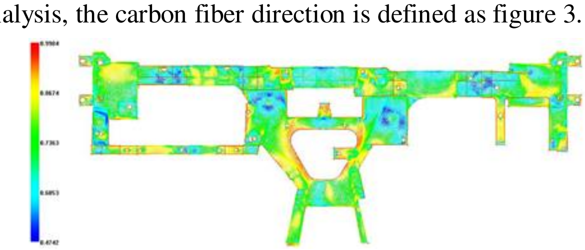


Figure 3. The carbon fiber direction of the component

Secondly, the material document used for analysis was fitted by Digimat.

Thirdly, the steering system mode analysis(figure 4) was carried out by Abaqus. The used analysis model was shown as figure 4a. The steering system was assembled to car body. Then the material document fitted from Digimat was imported to the model. The analysis result was shown in figure 4b and table 1.

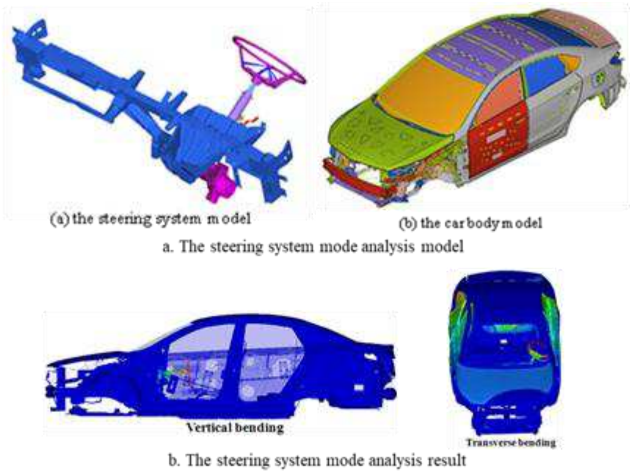


Figure 4. The steering system mode analysis

Table 1 The steering system mode analysis result

Analysis mode	Analysis result	Compared steel part
First Order Vertical Vibration (Hz)	22.6	34
First Order Transverse Vibration (Hz)	33.2	38

Although the analysis result of composite Steering column support assembly is lower than that of steel part, the NVH performance of the composite Steering column support assembly may still meet the requirement. Compared with traditional metal alloy materials, the viscoelastic matrix of the fiber-reinforced composite material can effectively improve the damping performance of the structure while ensuring the load-bearing capacity of the structure. Relevant literature has confirmed that the damping of fiber-reinforced composite materials is tens to hundreds of times that of metal materials, it not only controls the vibration and noise of the structure, but also plays an important role in prolonging the service time of the structure under cyclic load and impact[33].

When the exciting factor disappears, the vibration will eventually stop slowly due to damping. Damping is one of the important factors that affect the dynamic response. When the disturbance frequency is close to the system's natural frequency, the damping has a great influence on the amplitude, resulting in a decrease in vibration. The logarithmic decline rate can characterize the attenuation of the amplitude. The higher the damping performance, the greater the value of logarithmic decline rate, the greater the amplitude attenuation (Figure 5).The mathematical formulation of logarithmic decline rate can be expressed as equation (1).

$$\delta = \frac{1}{n}\ln\left(\frac{A_i}{A_{i+1}}\right) \quad (1)$$

In which, δ is logarithmic decline rate, n is vibration cycles index, A is amplitude.

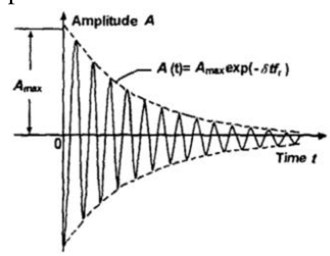


Figure 5. Displacement-time curve of damping vibration

4 Manufacturing of composite Steering column support assembly

By now, glass fibers and natural fibers are the most common fiber reinforced used in injection molding in the automotive industry. In order to make full use of the existing injection equipment as well as satisfy the performance requirement of Steering column support assembly, 30% carbon fiber reinforced PA66 was used to manufacture the component. Only the screw needed to be done some changes.

For Steering column support assembly body, due to larger and more complex shape, the gates of main body mold (Figure 6a) were defined by mold flow analysis to control the deviations of the part with respect to the design structure. While, the gates of the steering column bracket mold (Figure 6b) were designed directly.

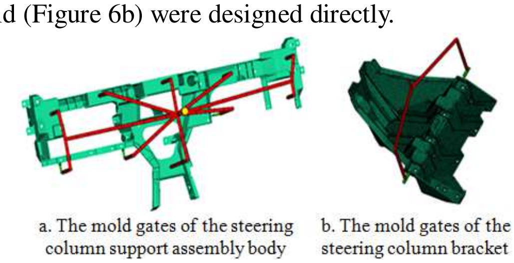


Figure 6. The mold gates of the Steering column support assembly

The detail manufacture process of CF reinforced PA66 Steering column support assembly was as follows: the raw plastic material was heated to remove absorbed water, and then was fed into the barrel. The barrel was heated to 300℃

to melt the material. The mold was heated to 100℃. The melted material was injected to the mold by the screw. The injection pressure in the barrel was divided into four sections as the screw moved forward, and then there were four different injection speeds, so that the material can be fulfilled all sections of the mold. The detail manufacturing parameters see table 2. The manufactured prototype see figure 7a. The weight of the two parts is 3.1kg for the Steering column support assembly body and 1.4kg for the steering column bracket.

Table 2. The manufacturing parameters of CF reinforcement PA66 Steering column support assembly

Manufacturing factors	Steering column support assembly body	Steering column bracket
Injection pressure(MPa)	First section: 95. Second section: 120. Third section: 100. Fourth section: 75	First section: 70. Second section: 95. Third section: 90. Fourth section: 60
Injection speed(m/s)	First section: 85. Second section: 72. Third section: 70. Fourth section: 40	First section: 65. Second section: 80. Third section: 75. Fourth section: 40
Clamping force (Tons)	2500	720
Holding pressure (MPa)	105	95
Holding pressure time (s)	10	5
Cooling time(s)	50	30
Injection temperature(℃)	285	285

In order to definite the steering system mode requirement, 40% GF reinforced PA66 with much lower mechanical properties (Table 3) than that of CF reinforced PA66 was chose to manufacture Steering column support assembly. Because of the same matrix, the manufacturing process for the GF reinforcement PA66 Steering column support assembly is similar to that of CF reinforcement PA66 Steering column support assembly (Table 4). The temperature for the barrel and mold is the same as that of CF reinforcement PA66 Steering column support assembly. Only the manufacturing parameters have a little difference. The manufacturing parameters see table 2. The manufactured prototype is shown as figure 7b. The weight of the two parts is 3.3kg for the Steering column support assembly body and 1.5kg for the steering column bracket.

Table 3. Mechanical property of composite materials

Composite Material	Density (g/cm^3)	Tensile Strength (Mpa)	Tensile Modulus (Gpa)	Flexural strength (Mpa)	Flexural modulus (Gpa)
PA66-30% CF	1.32	323	32.8	506	30.8
PA66-40% LGF	1.22	230	17	320	14

Table 4. The manufacturing parameters of GF reinforcement PA66 Steering column support assembly

Manufacturing factors	Steering column support assembly body	Steering column bracket
Injection pressure(MPa)	First section: 90. Second section: 120. Third section: 100. Fourth section: 70	First section: 85. Second section: 95. Third section: 80. Fourth section: 60
Injection speed(m/s)	First section: 80. Second section: 60. Third section: 60. Fourth section: 40	First section: 70. Second section: 80. Third section: 60. Fourth section: 50
Clamping force (Tons)	2500	720
Holding pressure (MPa)	105	95
Holding pressure time (s)	10	5
Cooling time(s)	50	30
Injection temperature(℃)	270	270

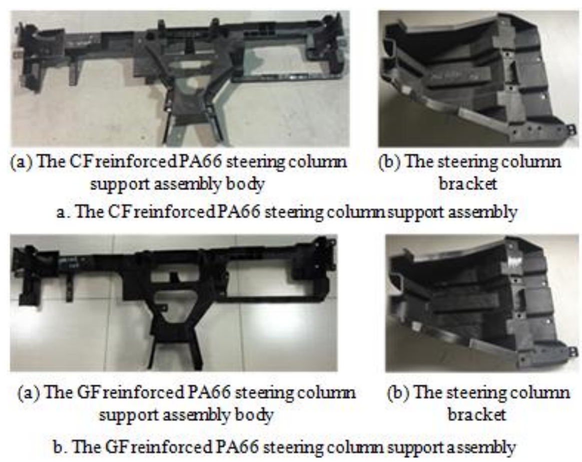


Figure 7. The composite steering column support assembly

5 Tests

By now, the damping value of this composite material component can't be test directly, as component size, material composition, material construction and so on would affect it. So we can't evaluate the effect of the damping property for this component directly. Then, by an indirect method that is comparing the steering system mode requirement of the composite component with that of the steel component, we can evaluate the effect of damping property.

Therefore, definition of the steering system mode requirement of the composite component is crucial. By the following test the steering system mode requirement was defined.

5.1 Steering system mode test

The steering system mode of CFRP Steering column support assembly should be tested and the mode analysis result should be verified to be reasonable. Therefore, the steering system mode test was performed. The test was carried out as follows: the CF reinforced PA66 Steering column support assembly was assembled to the car. Then four signal sensors were fixed on the four points of steering wheel showing in figure 8. The steering wheel was knocked by hammer. The resonance frequency was defined by the vibration signal sensed by the sensors, and the steering system mode was tested.

Figure 8. The steering system mode test

By comparing the analysis result and the test result (Table 5), the first order vertical bending frequency is same for the two results, and the first order transverse frequency for the analysis result is higher than that of the test result for 2.5 Hz which can satisfy the error requirement between the analysis result and the test result. Therefore, the analysis result can be good agreement with the test result for the steering system mode of the composite Steering column support assembly.

Table 5. The steering system mode test result

Vibration Mode	Test Result	Analysis Result
First Order Vertical bending (Hz)	22.6	22.6
First Order Transverse bending (Hz)	30.7	33.2

5.2 NVH test

In order to verify whether the CFRP Steering column support assembly with the steering system mode that is lower than that of steel part can satisfy the NVH requirement, NVH test under various conditions was conducted. The NVH test result shows that the noise (Figure 10 and Table 6) and vibration (Figure 11) performance of the test vehicle with the composite part is closed to that of the compared vehicle assembled with steel component. The NVH performance of CF reinforced PA66 Steering column support assembly can fulfil the requirement.

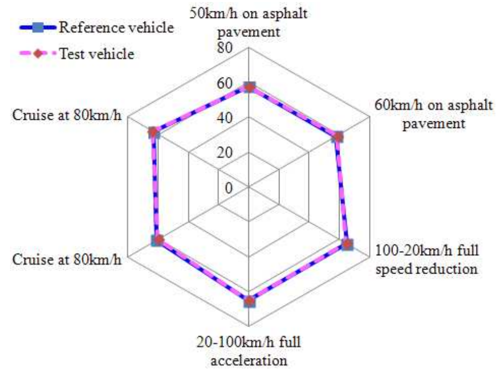


Figure 10. Interior noise test of CFRP Steering column support assembly[17]

Table 6. Interior noise test of CFRP Steering column support assembly [17]

Test Content		Test Vehicle	Reference Vehicle
Sliding Noise,	FLR (dBA)	61.13-54.89	61.1-53.7
80-30km/h	FLR(AI%)	130.66-94.29	131-94.2

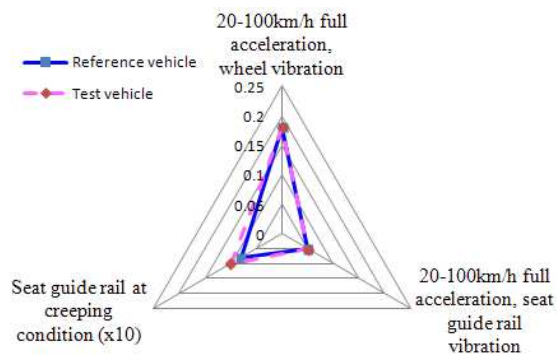


Figure 11. Vibration test of CFRP Steering column support assembly [17]

Although CFRP Steering column support assembly can satisfy NVH requirement, the steering system mode requirement can't be set. In order to determine the mode requirement, the resonance frequency of the composite steering column support system assembly must be measured. So the NVH test for glass fiber reinforced PA66 steering column support system assembly was conducted, as this part with much lower mechanical property would not pass the NVH test and the steering wheel would have resonance vibration under some frequency. The test result shows that the glass fiber composite Steering column support assembly can satisfy the noise requirement (Figure 12 and Table 7). For vibration result (Figure 13), only the steering wheel vibration acceleration which is 0.45g is much higher than that of compared steel part, and can't meet the requirement. At the speed of 47km/h, the steering wheel have obvious vibration along X and Y direction, and the resonance frequency is 19Hz (Figure 14a). The steering wheel also has obvious vibration at 66km/h and 100km/h along Z direction, and the resonance frequency is 27Hz (Figure 14b).

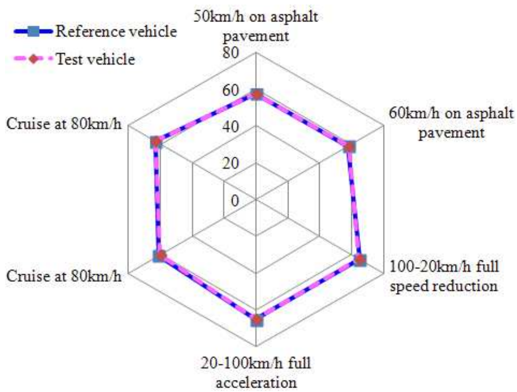


Figure 12. Interior noise test of GFC Steering column support assembly

Table 7. Interior noise test of GFC Steering column support assembly

Test Content		Test Vehicle	Reference Vehicle
Sliding Noise	FLR (dBA)	60.8-53.5	61.1-53.7
80-30km/h	FLR (AI%)	133.6-96.5	131-94.2

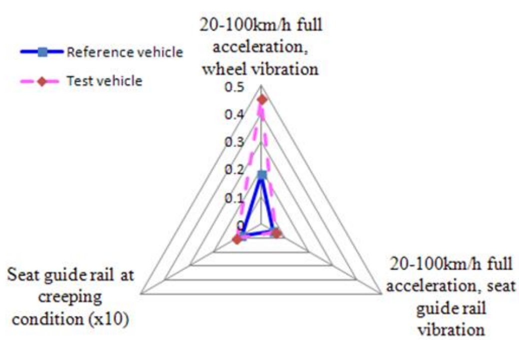
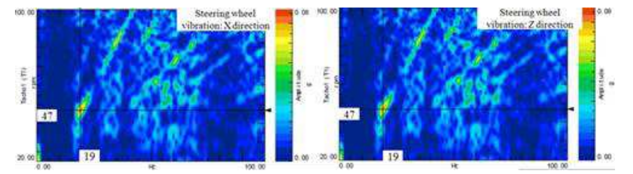
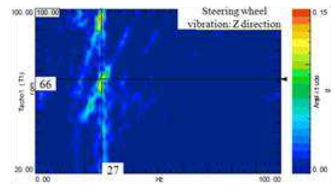


Figure 13. Vibration test of GFC Steering column support assembly



a. Steering wheel vibration of GFRC steering column support assembly at 47km/h



b. Steering wheel vibration of GFRC steering column support assembly at 66 km/h

Figure 14. Steering wheel vibration of GFC Steering column support assembly

6 Results and discussion

According to the resonance vibration frequency of glass fiber composite Steering column support assembly and the rule that the first natural frequency should keep more than 3Hz away from the resonance frequency, the steering system mode for composite Steering column support assembly of the EV is defined as follows: the first order vertical bending frequency should be higher than 22Hz, the first order transverse bending frequency should be higher than 30Hz. By comparing the defined steering system mode requirement and the steering system mode test result of CF reinforced PA66 Steering column support assembly (Table 8), we can see that the test result of the first order vertical bending mode is only higher for 0.6Hz than the defined requirement, and the difference for the first order transverse bending mode between the test result and the requirement is only 0.7Hz. In a word, the difference between the test result of the CFRP component that can satisfy the NVH performance requirement and the defined requirement is small, and we can conclude that the steering system mode requirement for this kind of composite Steering column support assembly is reasonable.

Table 8. The comparison of the definition and the test result

Vibration Mode	Steering system mode requirement definition	Test result
First Order Vertical bending (Hz)	22	22.6
First Order Transverse bending (Hz)	30	30.7

Then by comparing the steering system mode requirement for the composite Steering column support assembly with that of the steel part (Table 9), the value of the first order vertical bending mode of the composite Steering column support assembly is lower than that of the steel component for 12Hz which counts for 35.3% percent of the requirement for the steel component, and for the first order transverse bending mode, the requirement of the composite Steering column support assembly is lower for 8Hz (21.1% of the requirement of the steel component) than that of the steel Steering column support assembly (Figure 15). By this comparison, we can conclude that the damping property of composite material have above 21% percent effect on the NVH performance of composite component, and for the crucial bending mode, the effect is much higher, that is above 35% percent.

Table 9. The comparison of the steering system mode definition

Vibration Mode	Steering system mode requirement definition	Steering system mode requirement of steel part
First Order Vertical bending (Hz)	22	34
First Order Transverse bending (Hz)	30	38

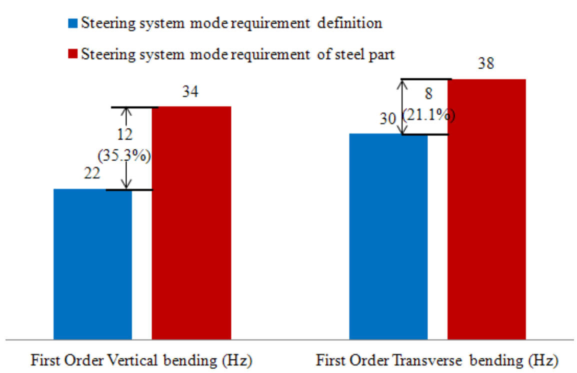


Figure 15. The comparison of the steering system mode definition

7 Conclusions

We studied the steering system mode definition of composite Steering column support assembly with a simple method. Due to the damping property of composite materials, the composite component with a significantly lower first natural frequency compared to metal component can be accepted with an equivalent or better NVH performance. However, it is very hard to test the damping value of composite component. Therefore, a simple method that is concurrent test approach was used to definite the steering system mode of composite Steering column support assembly. In the manufacturing step of the method, two kinds of composite that are CF reinforced PA66 Steering column support assembly and glass fiber reinforced PA66 Steering column support assembly were manufactured. The tests were concurrent conducted for the two kind parts. By the NVH test of glass fiber composite Steering column support assembly which would not satisfy the NVH performance requirement, we could get the resonance vibration frequency of steering wheel, and then the steering system mode of composite Steering column support assembly of EV was defined. Then by the steering system mode test and NVH test of CFRP Steering column support assembly which would satisfy the NVH performance requirement, the steering system mode analysis and the steering system mode requirement were verified. By comparing the steering system mode requirement, we can conclude that the damping property of this composite material have over 21% percent effect on the NVH performance of the composite Steering column support assembly.

7 Declaration

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Availability of data and materials

The datasets supporting the conclusions of this article are included within the article.

Authors' contributions

The author' contributions are as follows: Bo Liu, Jin-yan Wang and Ming-de Ding was in charge of the whole trial; Ming-de Ding wrote the manuscript; Zhen-hua Fan, Fu-qiang Zhai and Lu Li assisted with sampling and laboratory analyses.

Competing interests

The authors declare no competing financial interests.

Consent for publication

Not applicable

Ethics approval and consent to participate

Not applicable

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Appendix

Appendix and supplement both mean material added at the end of a book. An appendix gives useful additional information, but even without it the rest of the book is complete: In the appendix are forty detailed charts. A supplement, bound in the book or published separately, is given for comparison, as an enhancement, to provide corrections, to present later information, and the like: A yearly supplement is issue.

Figures

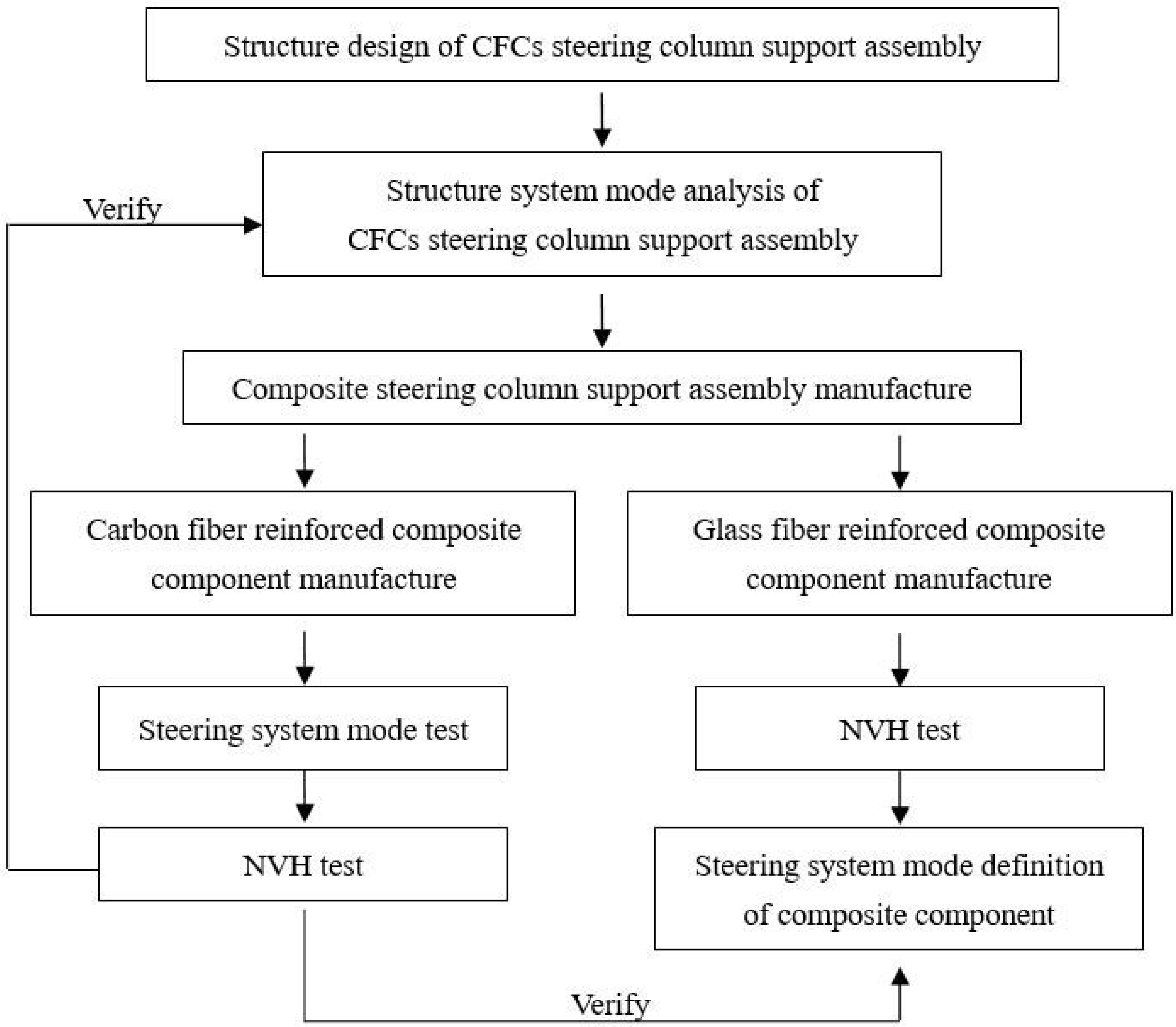


Figure 1

The concurrent test approach for composite Steering column support assembly

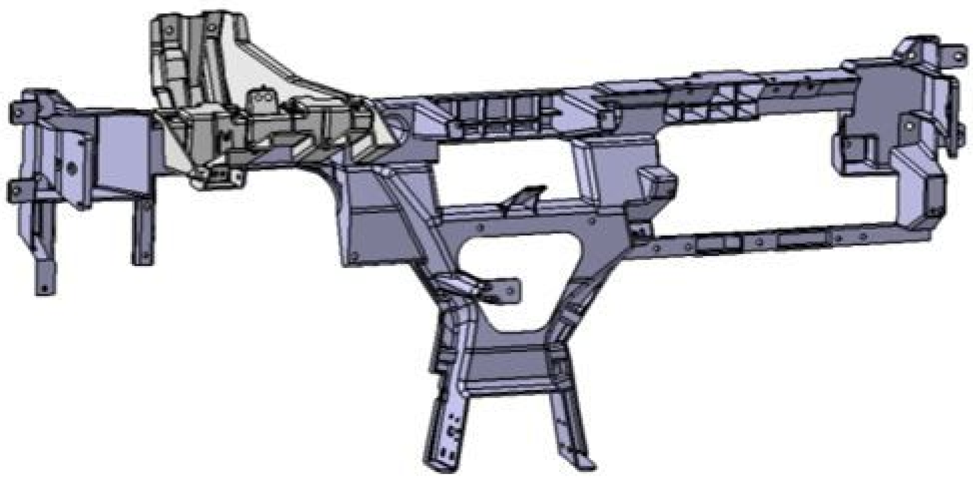


Figure 2

The detailed structure of the composite steering column support assembly

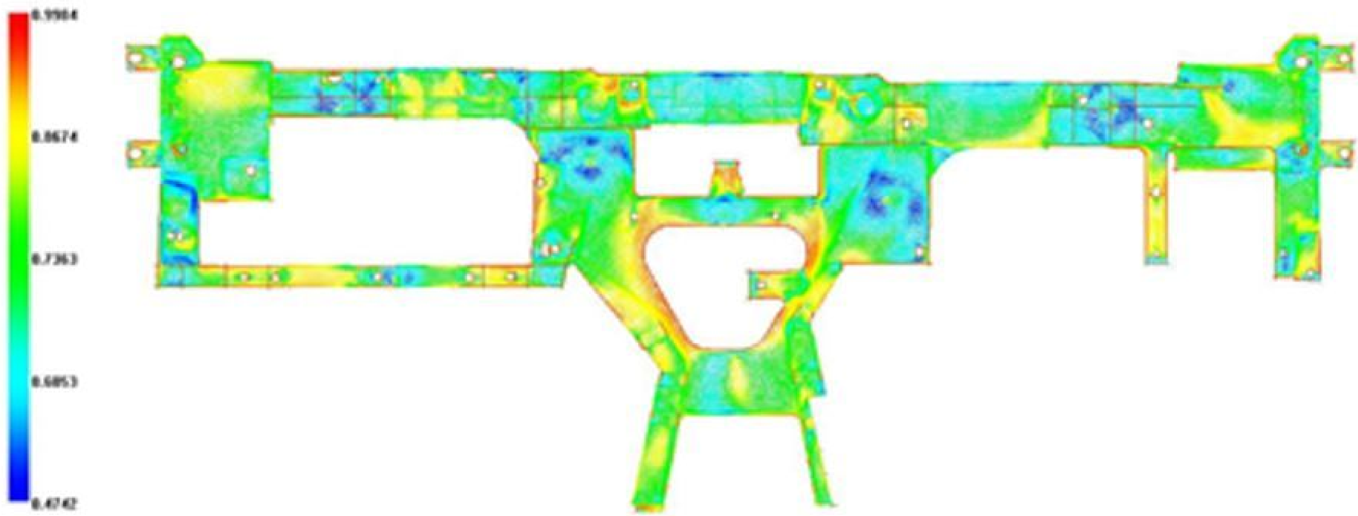


Figure 3

The carbon fiber direction of the component

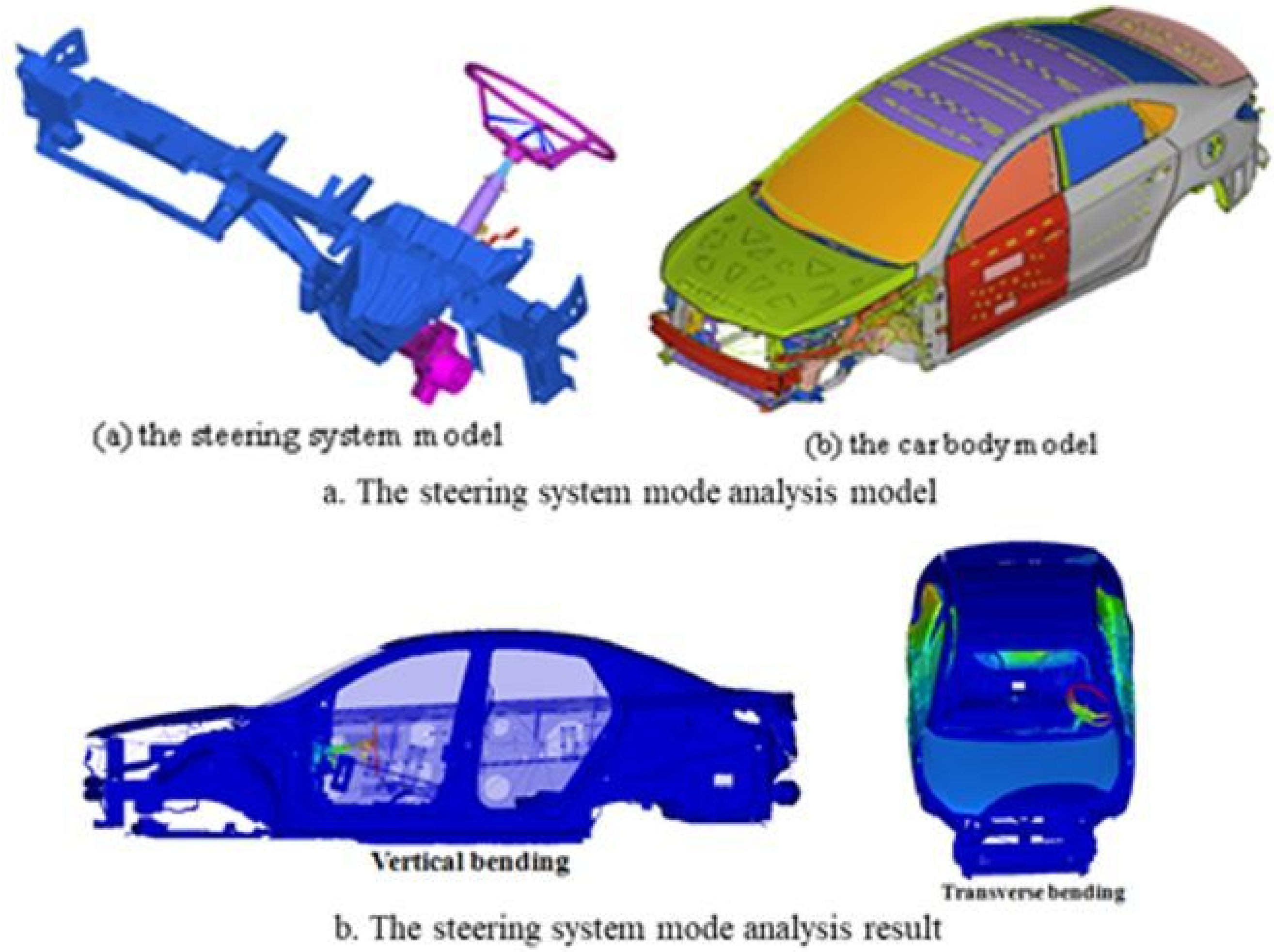


Figure 4

The steering system mode analysis

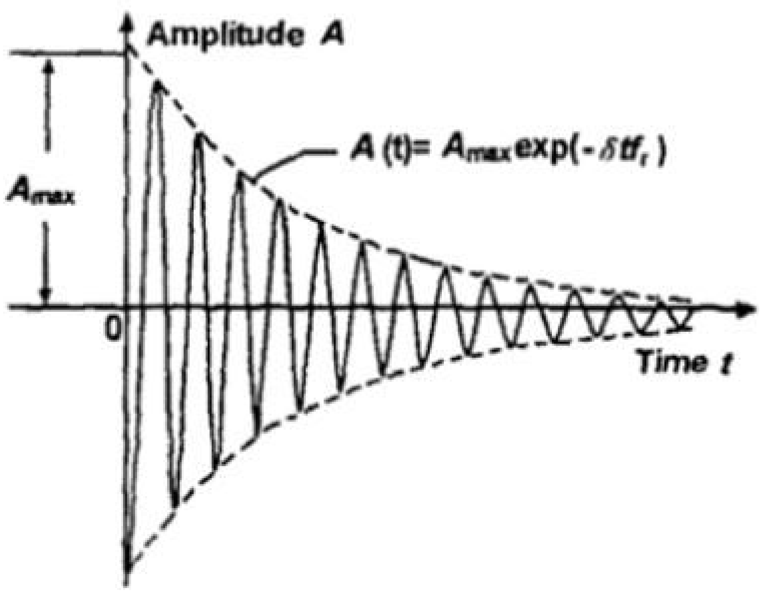


Figure 5

Displacement-time curve of damping vibration

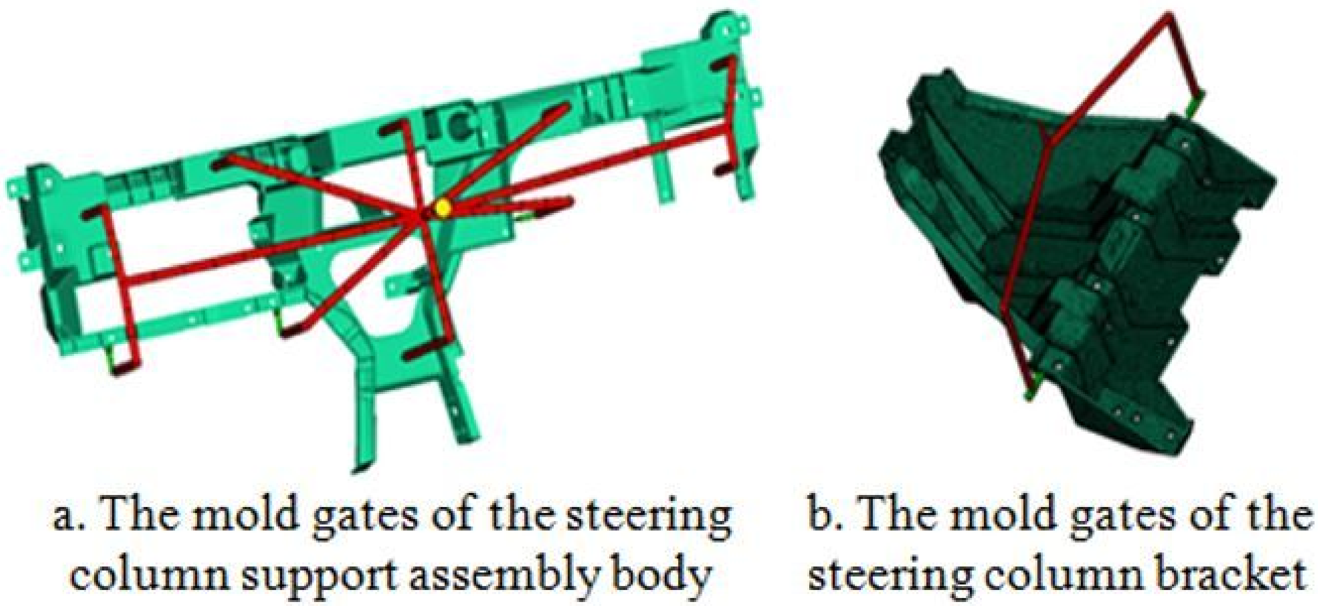


Figure 6

The mold gates of the Steering column support assembly

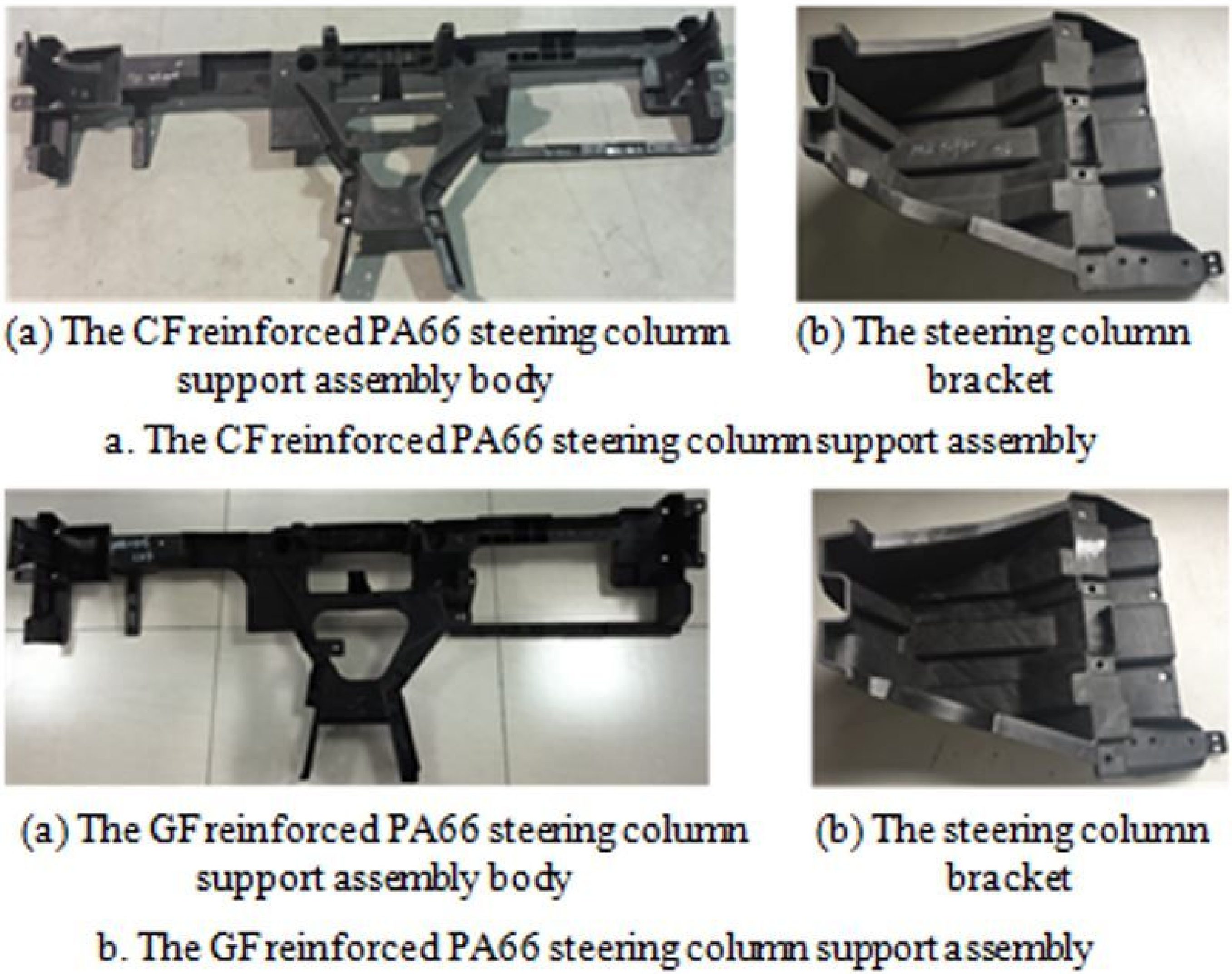


Figure 7

The composite steering column support assembly

Figure 8

The steering system mode test

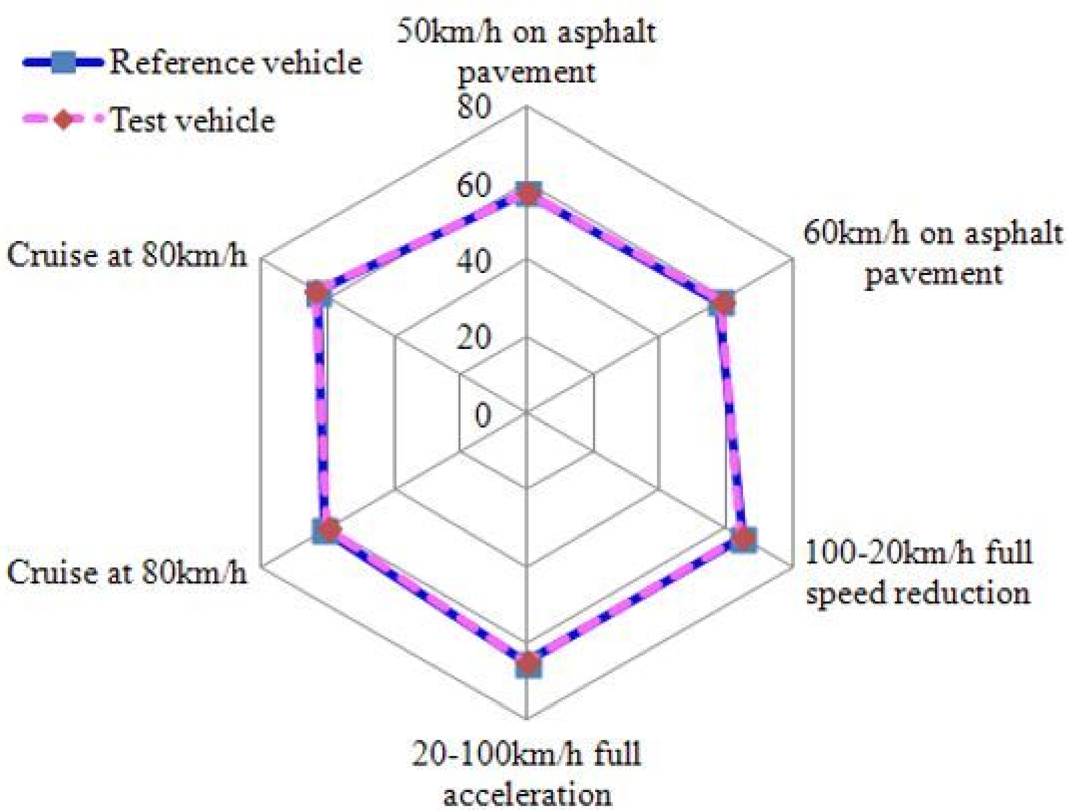


Figure 9

Interior noise test of CFRP Steering column support assembly[17]

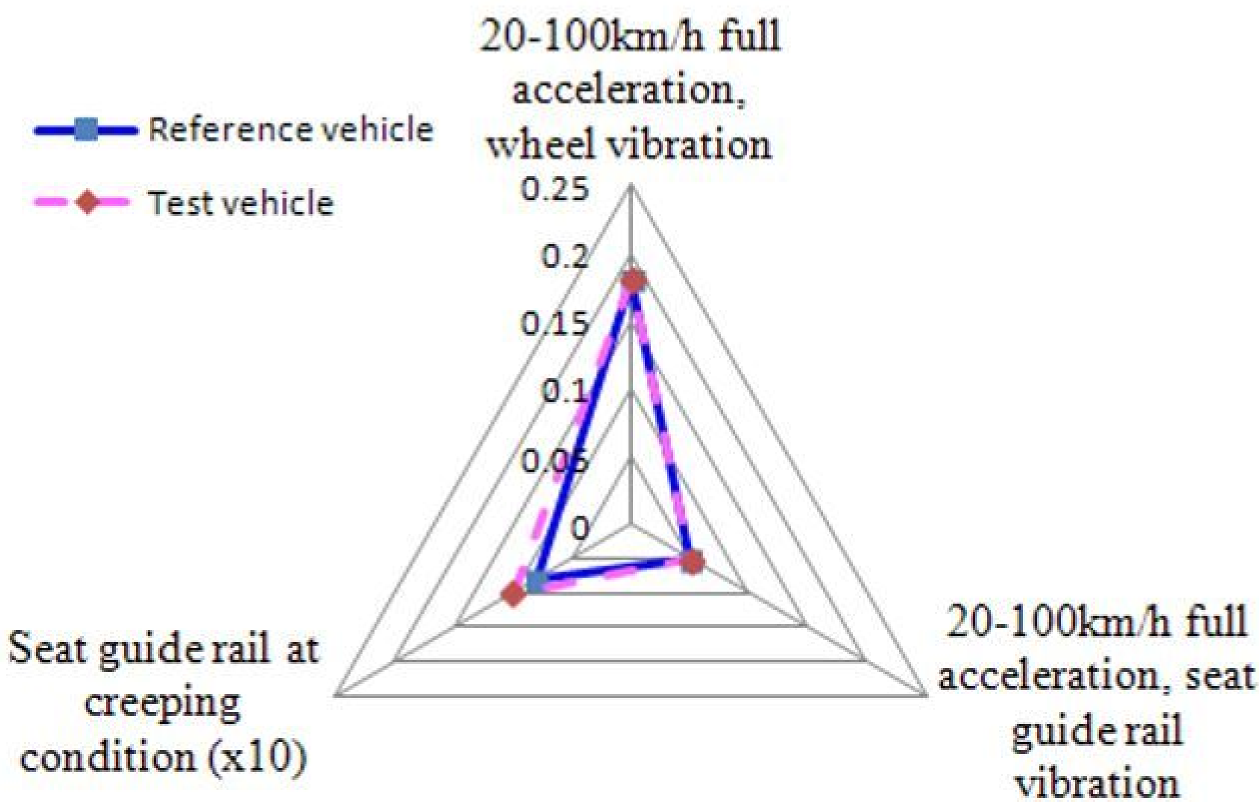


Figure 10

Vibration test of CFRP Steering column support assembly [17]

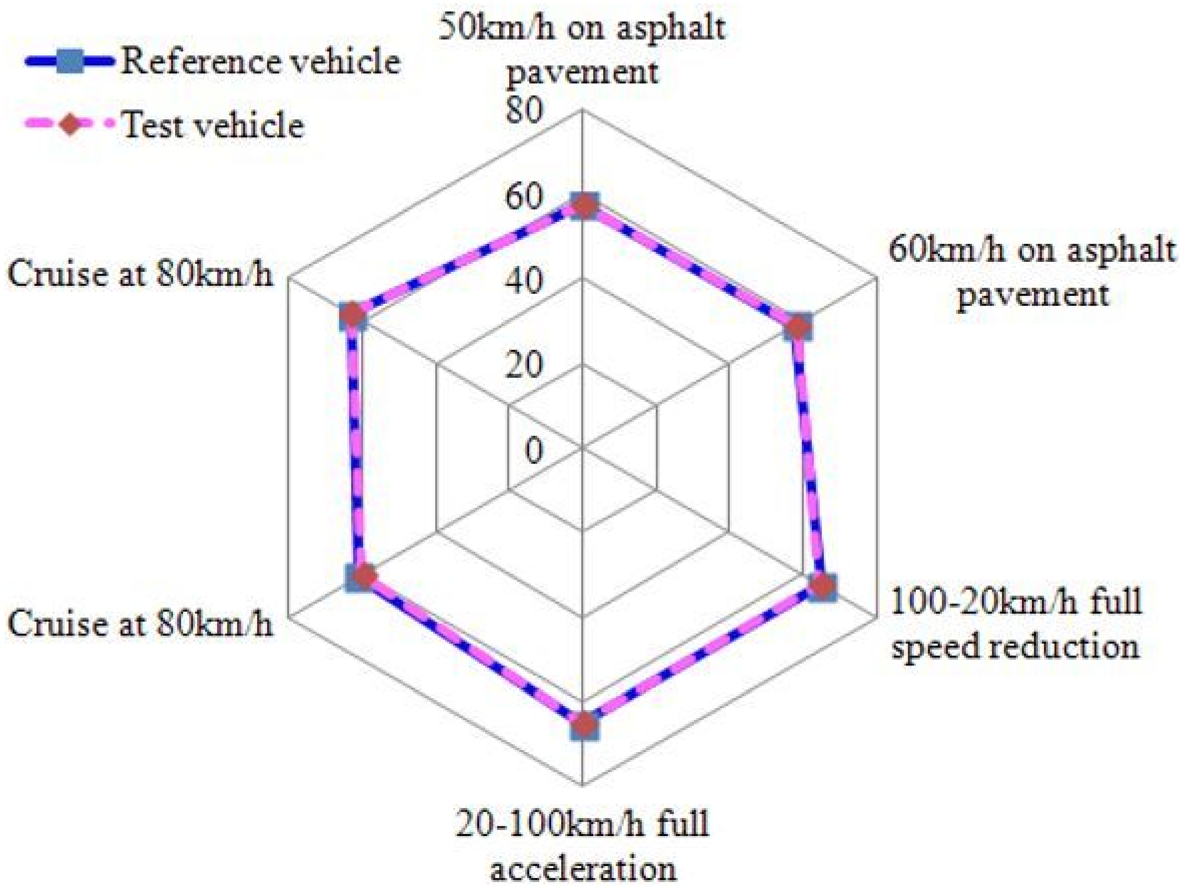


Figure 11

Interior noise test of GFC Steering column support assembly

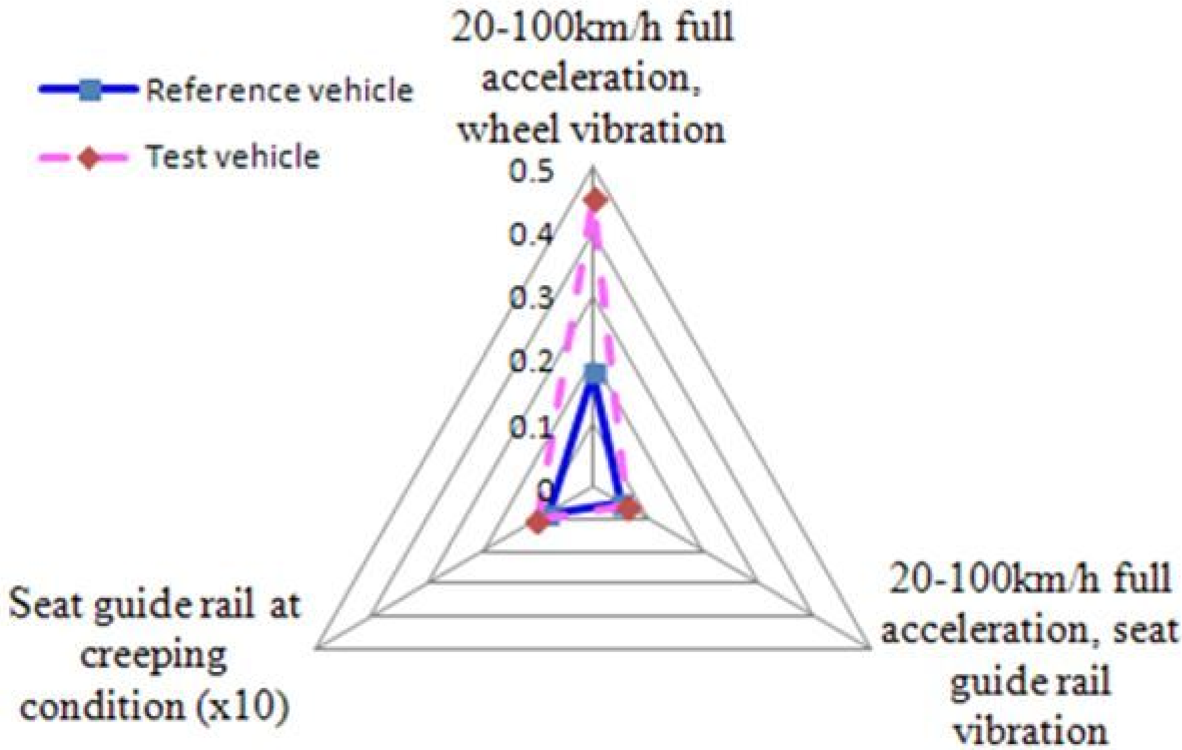
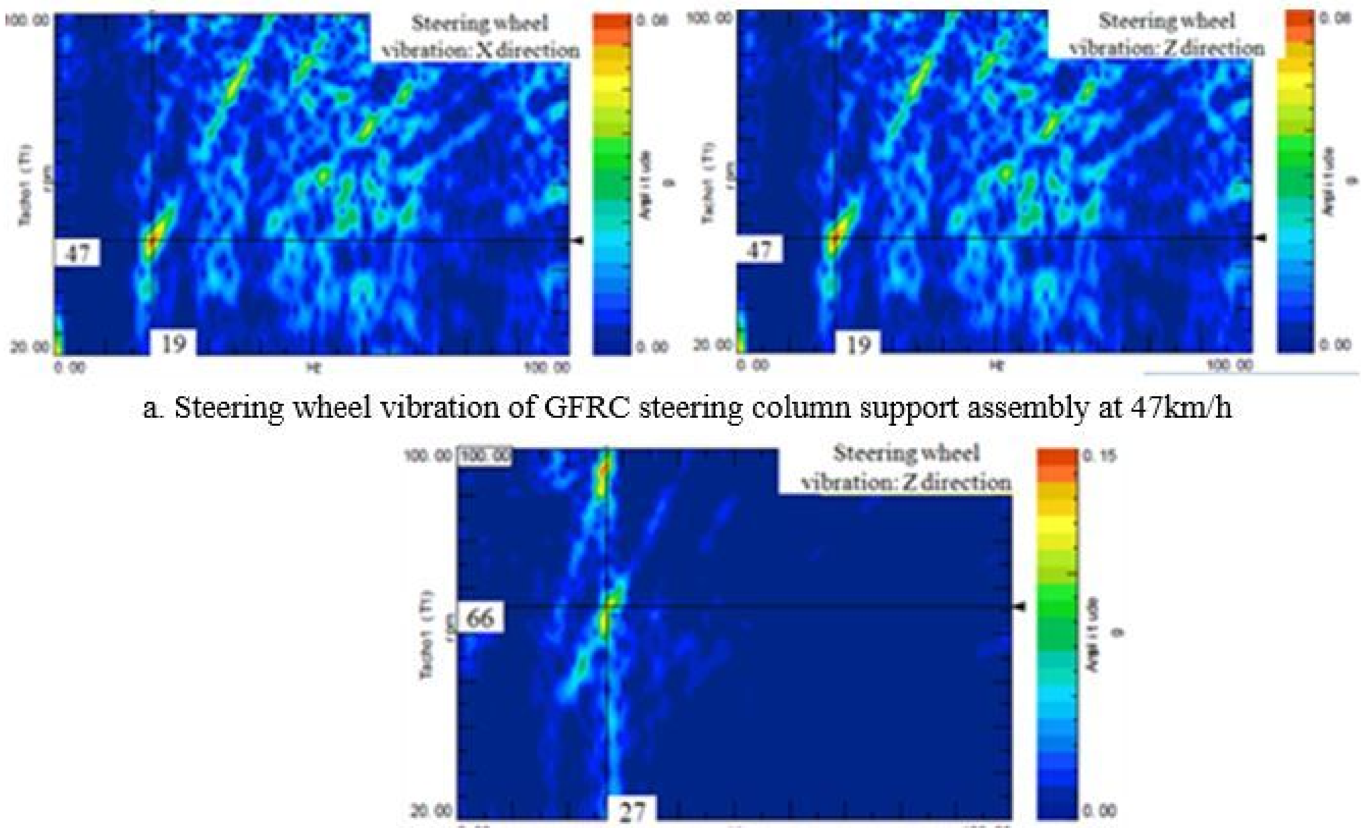


Figure 12

Vibration test of GFC Steering column support assembly



a. Steering wheel vibration of GFRC steering column support assembly at 47km/h

b. Steering wheel vibration of GFRC steering column support assembly at 66 km/h

Figure 13

Steering wheel vibration of GFC Steering column support assembly

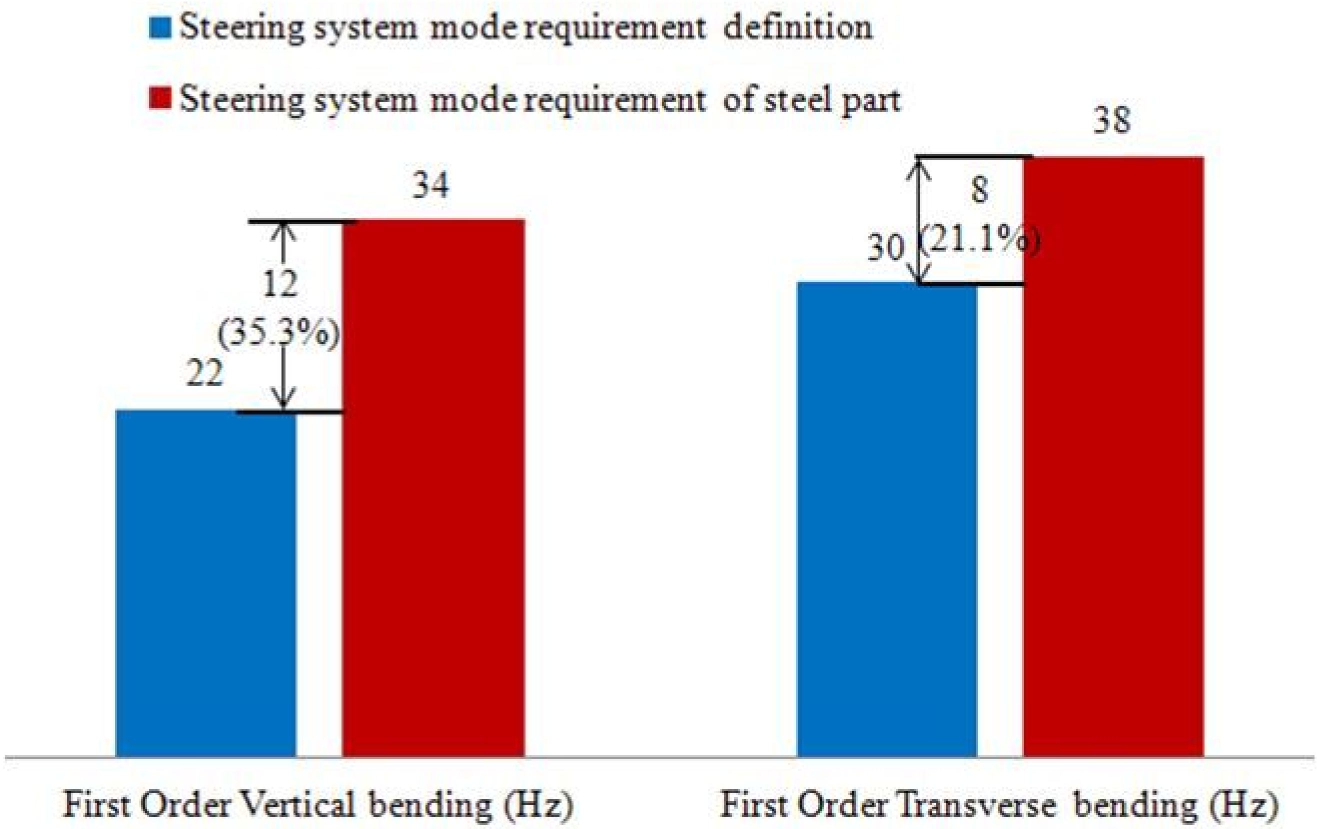


Figure 14

The comparison of the steering system mode definition