Research on Articulated Connector Load Identification Based on Dynamics

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Abstract. At present, articulated vehicles are developing rapidly in China and articulated connectors are important parts of articulated vehicles. In March 2016, CRRC Qiqihar Rolling Stock Co. LTD designed the GJ1 articulated connector. Due to the complexity of the articulated connector structure and stress distribution, it is necessary to study its loads in the application process. In this paper, the load identification of an articulated connector was mainly studied based on dynamic analysis. The dynamic model of the two coupling articulated vehicle was established. The relative motion relation of bump joints and the load conditions under some working conditions were analyzed. Finally, the finite element model was established and the static strength of the articulated connector was analyzed by means of the definition contact between the articulated connector parts. The results showed that the relative lateral displacement and relative side roll rotation angle of the concave and bump joints of the articulated connector were maximum in each working condition. More attention should be paid to the actual operation. The static strength of the main stressed parts of an articulated connector meet the design requirements. Since the material used for traction pin was not determined, high-strength tool steels T10 and T10A were recommended.

Keywords: Articulated vehicle; Articulated connector; Load; Dynamics; Structural strength.

1. Introduction

With the development of China’s railway freight transport, China is increasingly in need of efficient, fast and reliable means of transport. Because the articulated vehicle has the advantages of saving the number of bogies, making full use of axle load and shortening the distance of vehicle connection, the articulated vehicle has been gradually developed in China. Compared with ordinary rail vehicles, the front and rear cars of articulated vehicles share one bogie, which belongs to articulated bogies. The articulated connector is an important component of the articulated vehicle, the two ends of which are welded with the middle beam of the two vehicle bodies, and the bottom is located on the articulated bogie.

In March 2016, CRRC Qiqihar Rolling Stock Co., Ltd. designed the GJ1 articulated connector. Due to the special structure and complex stress situation of the articulated connector, it is necessary to study the load condition in the application process. It will not only contribute to the improvement of GJ1 articulated connector design and the evaluation of structural reliability, but also lay a solid foundation for the development of articulated vehicles.
At present, domestic and foreign research on articulated vehicles mainly focus on the dynamic performance of articulated vehicles [1-3] and the development of united articulated container flat vehicles [4,5]. Although the development of articulated vehicles started earlier in foreign countries, the research on articulated connectors is rarely reported in literatures in China and abroad. The French TGV used to use a articulated bogie to connect two cars without articulated connectors. In order to make up for the lack of research on articulated connectors, this paper studies the load problem of articulated connectors based on dynamics, and analyzes its structural strength.

Taking GJ1 articulated connector as the main research object, the dynamic model of the two coupling articulated vehicle is established, and the relative motion relation of bump joints and the load conditions under some working conditions are analyzed. Finally, the finite element model is established and the static strength of the articulated connector is analyzed by means of the definition contact between the articulated connector parts.

2. Articulated Connector Structure

GJ1 articulated connector mainly consists of three parts: a concave joint composition, a bump joint composition and a traction pin. The concave joint composition consists of the concave joint, the transfer sleeve, the support block, the slave plate, the slave plate gasket, the inclined wedge, the wedge block and the center pin. The bump joint composition is composed of the bump joint, the centripetal joint bearing, the retaining ring and the shaft sleeve. The ends of the concave and bump joints are welded with the adjacent middle beams of the two car bodies respectively. The concave and bump joints are connected through the traction pin of the lateral position, and the longitudinal force is transmitted through the transfer sleeve, from the plate, the inclined wedge and the wedge block. The structure of an articulated connector is shown in Figure 1, and its 3D model is shown in Figure 2.

![Figure 1. Structure of an articulated connector.](image)

![Figure 2. 3D model of an articulated connector.](image)

According to the design requirements, GJ1 articulated connector has a certain relative rotation angle between the bump joint and the concave joint, and its rotation angle parameters are shown in Table 1. The main design dimensions of GJ1 articulated connector are shown in Table 2.

| Direction of rotation angle | Value   |
|----------------------------|---------|
| Horizontal direction       | ±22°    |
| Vertical direction         | ±11°    |
| Rolling direction          | ±11°    |

Table 1. Relative rotation angle parameters of concave and bump joints.
Table 2. Main design sizes of articulated connectors.

| Name of parts                             | Size            |
|------------------------------------------|-----------------|
| Length×width of articulated connector    | 1156mm×538mm    |
| Height×width of bump joint               | 297mm×350mm     |
| Diameter of center plate of concave joint| Φ403mm          |

The concave and bump joints of GJ1 articulated connector are mainly made of C-grade cast steel. The mechanical properties of the newly developed modulated C-grade cast steel ZG25MnCrNiMo [6] are shown in Table 3.

Table 3. Mechanical properties of modulated C-grade cast steel ZG25MnCrNiMo.

| Material                  | Tensile strength | Yield strength |
|---------------------------|------------------|----------------|
| ZG25MnCrNiMo             | 790MPa           | 660MPa         |

3. Dynamic Analysis

3.1. Dynamic Model of Two Coupling Articulated Vehicle

The dynamic model of the two coupling articulated vehicle is taken the double united articulated container flat vehicle as the prototype, with three rotation K6 bogies and one GJ1 articulated connector between the two bodies, as shown in Figure 3.

Figure 3. Schematic diagram of two coupling articulated vehicle.

The worn wheel profiles and rail profiles, which are named LM and CHN60 [7] respectively, are used to simulate the wheel-rail relationship modeling. 78 force elements are used to simulate the wheel-rail force. Nominal wheel rolling circle radius is 420 mm, and FASTSIM algorithm is adopted to obtain the wheel-rail creep force.

According to the structural form of the rotary K6 bogie, Markers points, articulation and force elements among various parts are established, and the dynamic model of the rotary K6 bogie is created. The dynamic model of GJ1 articulated connector is simplified in part. The hinge is established between the parts to make sure that the articulated connector have relative motion relation only between the bump joint and the concave joint. The longitudinal, lateral and vertical forces are simulated by force element 5. The established K6 bogie model and GJ1 articulated connector model are imported into the vehicle model to establish the dynamics model of the two coupling articulated vehicle, as shown in Figure 4.

Figure 4. Dynamic model of two coupling articulated vehicle.

3.2. Relative Motion of Concave and Bump Joints

(1) Vehicle working conditions in a straight line

The operation condition of the vehicle in a straight line refers to that the vehicle passes through the straight line with stimulation at a certain speed, so as to investigate the relative displacement and relative angle between the concave and bump joints of the articulated connector. However, the relative rotation angle between concave and bump joints is very small under working conditions in a straight line, so the relative displacement is only investigated here.
In this paper, 5-level American spectral stimulation with five speed levels of 80, 90, 100, 110 and 120 km/h are applied and calculated. Figure 5 shows the calculation results of the articulated vehicle under working conditions in a straight line at the speed level of 80 km/h.

Figure 5. Relative motion relation between concave and bump joints at 80 km/h. Figure 5 shows that the relative lateral displacements of concave and bump joints are less than 10 mm and the relative vertical displacements are less than 6 mm. According to the above simulation method, the results of straight-line operation at speeds of 90, 100, 110 and 120 km/h are shown in Figure 6.

Figure 6. Relative motion relation of concave and bump joints at different velocity levels. As can be seen from Figure 6, the relative displacement between concave and bump joints of the articulated connector increases with the increase of velocity. The maximum lateral displacement reaches 21 mm and the maximum vertical displacement reaches 6.5 mm.

(2) Vehicle curve working conditions
First the changes of relative displacement and relative angle between concave and bump joints of articulated connector are studied when passing through the curve without rail stimulation. Then, the influences of different curve radii are analyzed to determine the curve radius with the worst performance. Finally, the rail stimulation is applied for analysis. In this paper, a total of 5 curve working conditions are set, as shown in Table 4.

Table 4. Curve working conditions.

| Working conditions | Curve radius /m | Curve outer rail superelevation /m | Length of circular curve /m | Length of transition curves /m | Length of straight line /m | Maximal allowable deficient superelevation /m | Curve passing speed/km·h⁻¹ |
|--------------------|-----------------|----------------------------------|----------------------------|-------------------------------|---------------------------|---------------------------------------------|---------------------------|
| 1                  | 600             | 0.1                              | 100                        | 100                           | 200                       | 0.11                                        | 80                        |
| 2                  | 800             | 0.1                              | 100                        | 100                           | 200                       | 0.11                                        | 90                        |
| 3                  | 1000            | 0.1                              | 100                        | 100                           | 200                       | 0.11                                        | 100                       |
| 4                  | 1200            | 0.1                              | 100                        | 100                           | 200                       | 0.11                                        | 110                       |
| 5                  | 1500            | 0.1                              | 100                        | 100                           | 200                       | 0.11                                        | 120                       |
The relative motion relation of concave and bump joints with a curve radius of 600 m, no rail stimulation and a running speed of 80 km/h is calculated, and the results are shown in Figure 7.

![Figure 7](image1.png)

**Figure 7.** Working conditions of the two coupling articulated vehicle.

It can be seen from Figure 7 that, when the vehicle passes through the curve, the relative horizontal rotation angle of concave and bump joints gradually increases, and then decreases after stabilization. The maximal relative horizontal rotation angle appears at the stage of over-circular curve, with the value of 2.1°. The maximal relative side roll rotation angle of concave and bump joints is 7.2°, which occurs when the vehicle runs out of the circular curve and enters the transition curve. The maximal relative lateral displacement of concave and bump joints is 30 mm.

It can be calculated that the relative motion of concave and bump joints varies with the curve radius when the articulated vehicle passes through the curve under five working conditions, as shown in Figure 8.

![Figure 8](image2.png)

**Figure 8.** Curve passing performance changes with curve radius.

As can be seen from Figure 8, when the curve radius is 600 m, the performance of articulated connectors is relatively poor. Therefore, in this paper, an American 5-level spectral stimulation is applied to the rail with a curve radius of 600 m, and the calculation results are shown in Figure 9.

![Figure 9](image3.png)

**Figure 9.** Curve passing performance of the two coupling articulated vehicle on a line with stimulation.

According to the analysis of the relative motion relation of the concave and bump joints of the articulated connector under the above straight and curve working conditions, the relative lateral
displacement and relative side roll rotation angle of the articulated connector concave and bump joints are maximum. It should be paid attention to load identification research in the future.

3.3. Load Analysis of Articulated Connectors
In this paper, we simulate a 10-km-long rail, including two curve lines with a radius of 1500 m and 1200 m respectively, and the American 5-level spectrum is applied as the rail stimulation. The articulated vehicle passes through the simulated rail at a constant speed of 120 km/h to record the longitudinal, lateral and vertical loads of the articulated connector.

Because the working condition of a vehicle in the actual running process is very complex, it is difficult for the simulation software to fully represent it. The rail types set in this study mainly consider the uniform working conditions under the straight line and curve conditions of a single track, and do not discuss the switching conditions, up and down slope, train marshalling and sliding in the depot, etc. Since the above conditions are ignored, the longitudinal load only reflects the load changes of the vehicle in coasting conditions, and the vertical load only reflects the load changes of the vehicle in horizontal working conditions.

The above conditions are simulated to obtain the loads of the articulated connector in three directions, and 16-level load spectra of longitudinal, lateral and vertical loads of the articulated connector are obtained after data processing, as shown in Table 5-7.

Table 5. Longitudinal load spectrum of articulated connectors.

| Level | Load amplitude (kN) | Frequency | Cumulative frequency |
|-------|-------------------|-----------|---------------------|
| 1     | 2.88              | 240       | 1612                |
| 2     | 8.65              | 217       | 1372                |
| 3     | 14.42             | 290       | 1155                |
| 4     | 20.18             | 205       | 865                 |
| 5     | 25.95             | 208       | 660                 |
| 6     | 31.72             | 144       | 452                 |
| 7     | 37.48             | 115       | 308                 |
| 8     | 43.25             | 83        | 193                 |
| 9     | 49.01             | 44        | 110                 |
| 10    | 54.78             | 25        | 66                  |
| 11    | 60.55             | 14        | 41                  |
| 12    | 66.31             | 10        | 27                  |
| 13    | 72.08             | 5         | 17                  |
| 14    | 77.85             | 3         | 12                  |
| 15    | 83.61             | 3         | 9                   |
| 16    | 89.38             | 6         | 6                   |

Table 6. Lateral load spectrum of articulated connectors.

| Level | Load amplitude (kN) | Frequency | Cumulative frequency |
|-------|-------------------|-----------|---------------------|
| 1     | 11.98             | 565       | 1241                |
| 2     | 35.93             | 26        | 676                 |
| 3     | 59.88             | 55        | 650                 |
| 4     | 83.83             | 58        | 595                 |
| 5     | 107.78            | 80        | 537                 |
| 6     | 131.73            | 87        | 457                 |
| 7     | 155.68            | 93        | 370                 |
| 8     | 179.63            | 73        | 277                 |
| 9     | 203.58            | 81        | 204                 |
| 10    | 227.53            | 46        | 123                 |
| 11    | 251.48            | 28        | 77                  |
Table 7. Vertical load spectrum of articulated connector.

| Level | Load amplitude (kN) | Frequency | Cumulative frequency |
|-------|---------------------|-----------|---------------------|
| 1     | 4.44                | 898       | 1367                |
| 2     | 13.32               | 59        | 469                 |
| 3     | 22.21               | 29        | 410                 |
| 4     | 31.09               | 32        | 381                 |
| 5     | 39.97               | 60        | 349                 |
| 6     | 48.86               | 68        | 289                 |
| 7     | 57.74               | 57        | 221                 |
| 8     | 66.62               | 63        | 164                 |
| 9     | 75.50               | 28        | 101                 |
| 10    | 84.39               | 28        | 73                  |
| 11    | 93.27               | 22        | 45                  |
| 12    | 102.15              | 9         | 23                  |
| 13    | 111.04              | 8         | 14                  |
| 14    | 119.92              | 3         | 6                   |
| 15    | 128.80              | 1         | 3                   |
| 16    | 137.69              | 2         | 2                   |

From the above results, it can be seen that compared with AAR standard, the simulation results of lateral loads can reflect the situation of vehicle lateral loads in practical application. Vertical loads under coasting conditions and vertical loads under horizontal rail working conditions are far less than loads of articulated connectors in the cases of AAR standard. Longitudinal loads are mainly affected by vehicle starting acceleration, brake deceleration, longitudinal impact and shunting conditions, while vertical loads are mainly influenced by horizontal working conditions and upper and lower slope conditions.

The analysis of loads of articulated connectors not only provides the theoretical reference for the follow-up line test, but also offers data for the study of the relation between simulated loads and measured loads.

4. Structural Strength of Articulated Connectors

An articulated connector is a key component of an articulated vehicle, and its stress is complex. In order to ensure the safety of an articulated vehicle during operation, the static strength of articulated connector should be analyzed.

4.1. Finite Element Model of Articulated Connectors

Finite element method is used to analyze the static strength of the structure. Considering that the contact force in the contact area of articulated connector parts is difficult to be calculated manually and the stress distribution in the contact area is special, the finite element model of an articulated connector is established by the contact method in this paper.

The Hypermesh software is used to divide the finite element of the parts of the 3D model of an articulated connector. Solid187 is selected as the unit type and 10 mm as the mesh size. The definition of contact pairs between parts of GJ1 articulated connector is shown in Figure 10. The global finite element model of GJ1 articulated connector is established, as shown in Figure 11.
4.2. Load and Working Conditions

According to the load parameters of static strength analysis of GJ1 articulated connector, 8 working conditions of calculation simulating the actual operation are designed, as shown in Table 8.

| Working condition                 | Load                          | Load amplitude (kN) |
|----------------------------------|-------------------------------|----------------------|
| Tensile working condition        | Longitudinal tensile load     | 3430                 |
| Compression Working condition    | Longitudinal compression load | 4450                 |
| Vertical working condition       | Vertical load                 | 1200                 |
| Horizontal working condition     | Lateral load                  | 250                  |
| Center plate loading condition   | Core plate longitudinal load  | 250                  |
| Curve condition                  | Lateral load + Vertical load  | 250+1200             |
| Traction acceleration condition  | Longitudinal tensile load + Core plate longitudinal load + Vertical load | 3430+250+1200 |
| Braking deceleration condition   | Longitudinal compression load + Core plate longitudinal load + Vertical load | 4450+250+1200 |

4.3. Load and Constraint Position

For longitudinal-tensile and longitudinal-compression loads, the positions of loads and constraints are applied to the positions of concave and bump joints at both ends of the articulated connector and the welding position of the vehicle beam, as shown in Figure 12.

In the process of practical application, connectors at both ends of the welding joints on the car body centre sill, form similar to a cantilever beam structure, so the restrictions are applied at both ends of the connector, loads are applied on the joints connectors in center plate parts, namely counterforce.
from bogie bottom center plate to the upper center plate of an articulated connector. Vertical loads and constraints applied position are shown in Figure 13.

![Figure 12. Load and constraint position of longitudinal loads.](image)

The longitudinal force loading of the center plate is similar to the vertical force loading. Constraints are applied at both ends of the articulated connector and longitudinal loads are applied at the center plate, i.e. loads are applied at the side edge of the center plate, as shown in Figure 14.

![Figure 13. Load and constraint position of vertical loads.](image)

Lateral loads are formed by the centripetal force of articulated bogie acting on the center plate of articulated connector and the centrifugal force of the car acting on both ends of articulated connector when the vehicle passes through the curve. Constraints are applied at both ends of the articulated connector and lateral loads are applied at the side edge of the center plate, as shown in Figure 15. Curve condition, traction acceleration condition and brake deceleration condition are applied to the articulated connector according to the combination of load conditions.
4.4. Analysis of Calculation Results

The maximum equivalent stress calculated under each working condition is listed in Table 9, and the stress nephogram of the part under maximum stress working condition is shown in Figure 16.

Table 9. Maximum stress of main parts of articulated connectors under various working conditions (MPa).

| Working condition | Bump joints | Concave joints | Traction pin |
|-------------------|-------------|----------------|-------------|
| 1                 | 704.9       | 689.1          | 1143.7      |
| 2                 | 607.2       | 585.7          | 344.1       |
| 3                 | 210.9       | 236.8          | 243.0       |
| 4                 | 53.5        | 163.5          | 212.3       |
| 5                 | 50.6        | 50.9           | 212.5       |
| 6                 | 159.1       | 287.2          | 247.3       |
| 7                 | 704.6       | 693.6          | 1151.7      |
| 8                 | 607.1       | 680.0          | 377.2       |

The above calculation results show that under each working condition, the maximum equivalent stress of concave and bump joints of an articulated connector is lower than the allowable stress of material 710 MPa, and the strength distribution is more reasonable, meeting the requirements of TB/T1335-1996 “Specification for Strength Design and Test Identification of Railway Vehicles”. The traction pin shows great stress under the tensile and traction acceleration conditions. CRRC Qiqihar Rolling Stock Co., Ltd. has not determined the material used for the traction pin. Since the stress has exceeded 1100 MPa, it is recommended to use tool steel T10 and T10A with yield strength up to 1300 MPa for traction pins.

5. Conclusions

(1) According to the dynamic analysis of the two coupling articulated vehicle, the relative lateral displacement and relative side roll rotation angle of the concave and bump joints of the articulated connector are maximum in each working condition, so it should be paid attention to load identification research in the future.
(2) Compared with AAR standard, the simulation results of lateral loads of an articulated connector can reflect the situation of lateral loads of a vehicle in practical application. Longitudinal loads of an articulated connector is mainly affected by the starting acceleration, braking deceleration, longitudinal impact and shunting conditions, while vertical loads are mainly affected by the horizontal working conditions and the upper and lower slope conditions.

(3) According to the structural strength analysis of an articulated connector, the static strength of concave and bump joints and the main stressed parts of an articulated connector meet the design requirements. Since the material used for traction pin is not determined, high-strength tool steels T10 and T10A are recommended.

(4) The analysis of loads of articulated connectors in this paper provides the theoretical reference for the follow-up line test. Load identification of articulated connectors will be studied in the future.

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