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Using STAR-CCM+ Software in Aerodynamic Performance of Bogies under Crosswind Conditions

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Abstract

INTRODUCTION: STAR-CCM+ is a CFD software that uses continuum mechanics numerical techniques and is a tool for thermodynamic and fluid dynamics analysis. STAR-CCM+has expanded the functions of surface treatment, such as surface wrapper, surface remesh, and volume mesh generation.With the increase of train speed, the aerodynamic phenomena become more prominent, and the aerodynamic phenomena of high-speed trains in crosswind environment become more complicated.
OBJECTIVES: Bogie is an important part of high-speed train. It is of great significance to study the aerodynamic performance Three groups of trains operating in a strong wind environment are modeled, and the surface pressure distribution characteristics of the car body and bogie, as well as the aerodynamic and aerodynamic torque distribution characteristics of each car and bogie, are analyzed when the train operates at 350km/h under a Class 12 crosswind condition.
RESULTS: The results of the study show the variation rules of surface pressure, aerodynamic force and aerodynamic moment of the car body and bogie with wind speed.
CONCLUSION: The windward surface pressure of the vehicle body increases linearly with the increase of wind speed, and the surface pressure of the roof and leeward side decreases linearly with the increase of wind speed.

Keywords: crosswind, high-speed trains, bogie, aerodynamic force, aerodynamic moment

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1. Introduction

The bogie is an important part of the high-speed train, which not only carries the high-speed train through the curve, but also plays the role of traction, braking and shock absorption. The existence of bogies causes abrupt changes in the profile geometry of high-speed trains and causes many aerodynamic phenomena. A cross wind is a wind with a 90° Angle between the direction of the wind speed and the direction of the train. The aerodynamic phenomena of high-speed train operation under cross-wind environment are complicated.

There are few researches on the aerodynamic performance of high-speed train bogies under cross-wind conditions at home and abroad[1]-[11]. HUANG Zundi et al. studied the aerodynamic changes of the bogies of EMU running across lines under the action of cross wind. The study was only carried out under one working condition with wind speed of 10m/s and speed of 400km/h. The research results showed that the impact of EMU running speed on the bogies resistance was greater than the wind speed, and the bogies of intermediate vehicles received greater resistance[12]. The research work only analyzed the aerodynamic force, not the pressure distribution and aerodynamic moment, but also analyzed the aerodynamic characteristics under different wind speeds.

In this paper, the aerodynamic performance of bogies is studied by using 3 train units as the model. The two types of bogies selected in the model are power bogies and unpower bogies. The wind speed selected is from class 7 to 12 wind speed, and the speed of high-speed train is 350km/h. The aerodynamic performance of the bogie is analyzed from three aspects: surface pressure distribution, aerodynamic force and aerodynamic moment.

2.Set calculation model

2.1 STAR-CCM+ software introduction

STAR-CCM+ is a CFD software that uses continuum mechanics numerical techniques and is a tool for thermodynamic and fluid dynamics analysis. STAR-CCM+has expanded the functions of surface treatment, such as surface wrapper, surface remesh, and volume mesh generation. The generated volume meshes include polyhedral, tetrahedral, trim, etc. During the calculation process, real-time monitoring of vector, scalar, and result statistics can be achieved, while achieving high practicality in post-processing data of engineering problems, high-performance fluid analysis, complexity of analysis objects, and expansion of user level range. Due to the use of continuum mechanics numerical techniques, STAR-CCM+ can not only perform fluid analysis, but also analyze other physical fields such as structures.

2.2 Calculated working condition

The calculated working conditions in this paper are shown in Table 1.

Table 1. Calculation Condition Settings

No	Train running speed （km/h）	Wind scale	Wind speed （m/s）	Wind direction angle
1	350	7	13.8m/s	90°
2		8	17.1m/s	
3		9	20.8m/s	
4		10	24.5m/s	
5		11	28.5m/s	
6		12	32.6m/s	

2.3 Calculate the region and boundary conditions

The setting of calculation domain and boundary condition of numerical simulation under cross-wind condition is shown in Figure 1, and the setting of calculation domain size is the same as that of open-line cycling condition. In the calculation domain boundary condition setting, the air domain incoming flow direction is set as the speed inlet, where the inlet wind speed is the train running speed. The right side of the train running direction is set as the speed entrance, where the inlet wind speed is the cross wind speed; The upper, left and rear planes of the train are provided with pressure exits; The ground and the train surface are set as non-slip walls. The distance between the head of the train and the speed inlet and the distance between the rear of the train and the pressure outlet are consistent with the setting of the calculation of the open line bicycles.

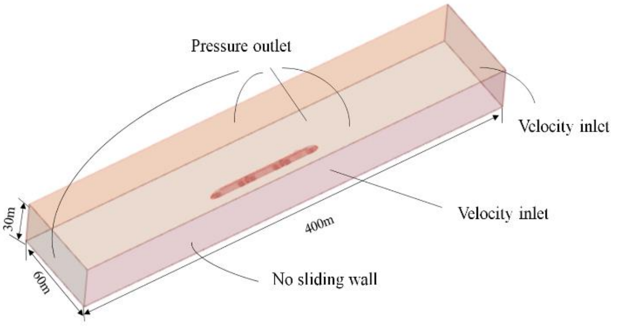
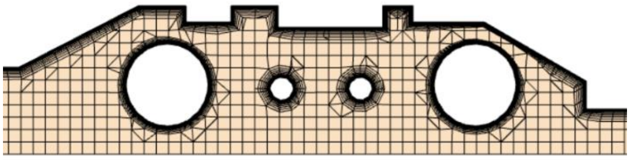


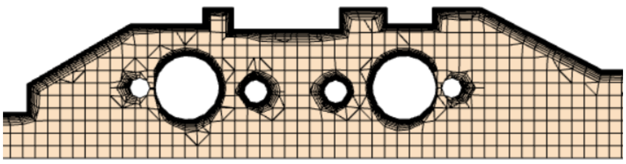
Figure 1. Cross-wind condition calculation area and boundary condition setting

3.Computational grid presentation

This model is a 3-unit EMU, and there are two types of bogies set on the vehicle body, namely bogies with power and bogies without power. The grid is divided according to the calculation area. The grid of the calculation area around the bogies is shown in Figure 2.



(a) Grid display of power bogie calculation domain



(a) Grid display of the calculation domain of unpowered bogies

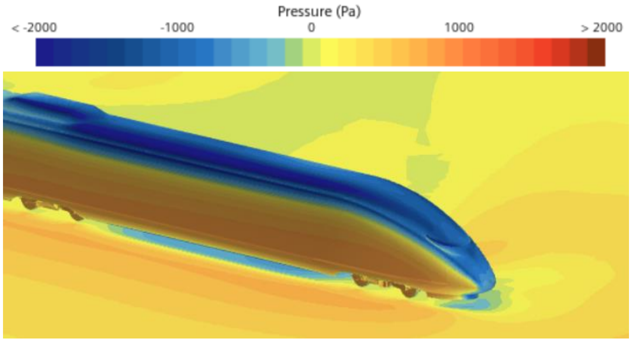
Figure 2. Shows the grid of calculation domain around the bogie

4. Surface pressure characteristics of high-speed train bogies under cross wind conditions

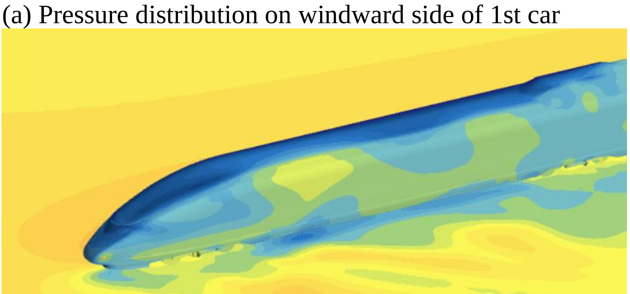
4.1 Surface pressure characteristics of high-speed train body under cross wind conditions

In order to study the train surface pressure distribution when the train runs under cross-wind conditions, Figure 3 shows the train surface pressure distribution diagram when a single train runs at 350km/h and the wind speed is 32.6m/s.

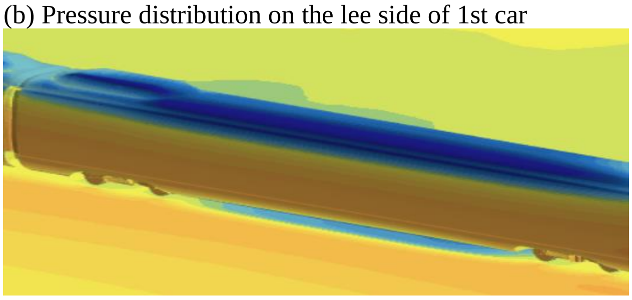
As can be seen from the figure, the body surface pressure on the windward side of the train is mainly positive pressure, while the body surface pressure on the leeward side is mainly negative pressure, and the roof surface pressure is also mainly negative pressure.



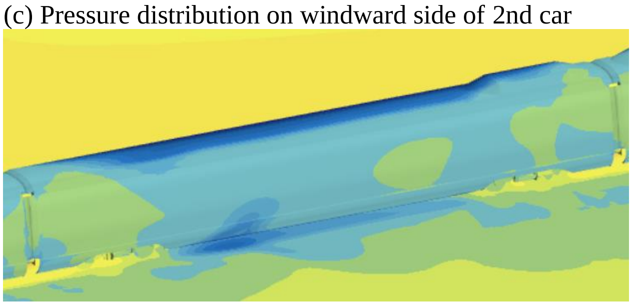
(a) Pressure distribution on windward side of 1st car



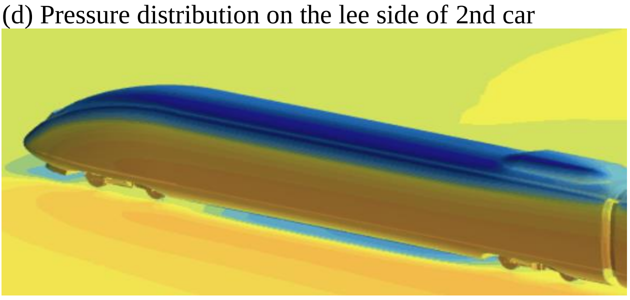
(b) Pressure distribution on the lee side of 1st car



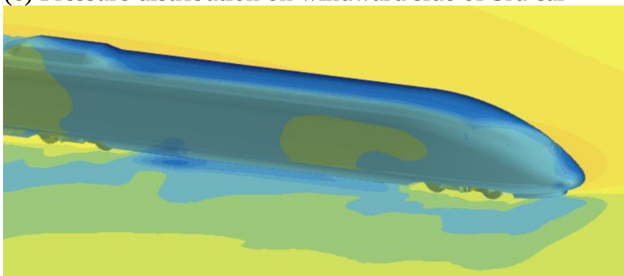
(c) Pressure distribution on windward side of 2nd car



(d) Pressure distribution on the lee side of 2nd car



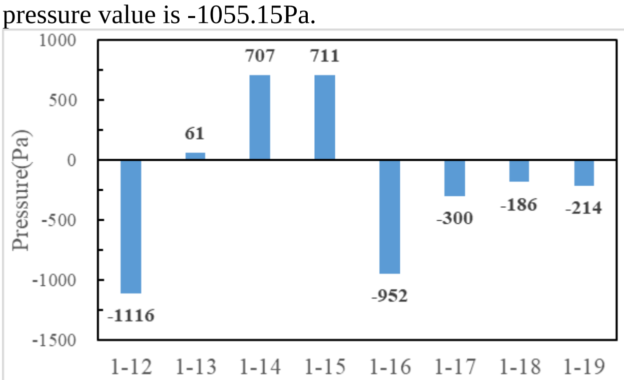
(e) Pressure distribution on windward side of 3rd car



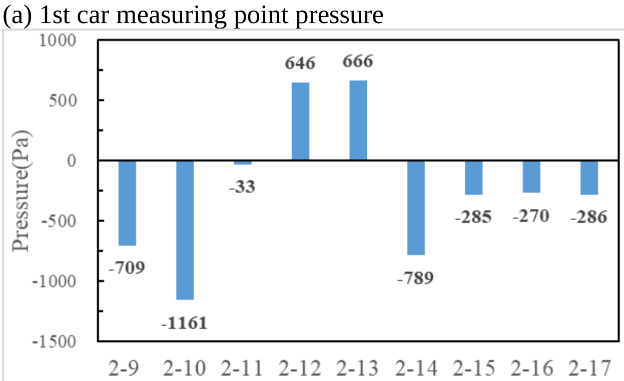
(f) Pressure distribution on the lee side of 3rd car

Figure 3. Body surface pressure distribution

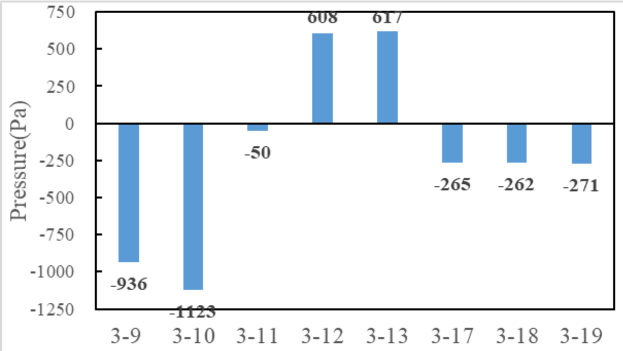
Figure 4 shows the comparison of pressure at various measuring points on the body surface when the cross wind speed is 32.6m/s. It can be seen that the top and leeward side of the body are negative pressure, while the windward side of the body is positive pressure. The maximum positive pressure and negative pressure at measuring points 1-15 and 3-10 appear respectively, and the pressure values are 711.35Pa and -1122.54Pa. The pressure of the measurement points of the locomotive streamline is negative, and the maximum negative pressure appears at the front car window 1-10, and the pressure value is -1055.15Pa.



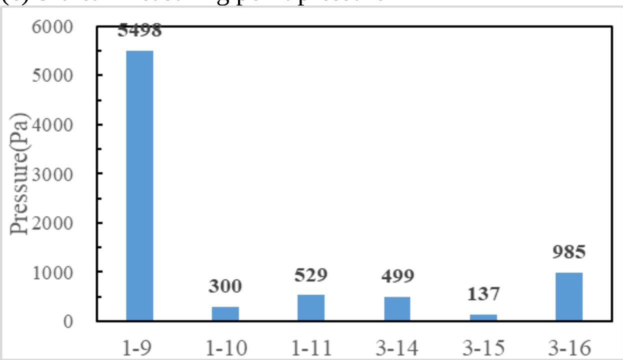
(a) 1st car measuring point pressure



(b) 2nd car measuring point pressure



(c) 3rd car measuring point pressure



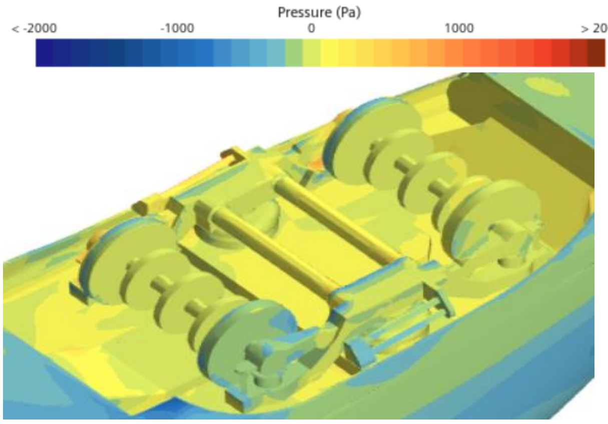
(d) The streamlined section measuring point pressure

Figure 4. Comparison of pressure values at body measuring points

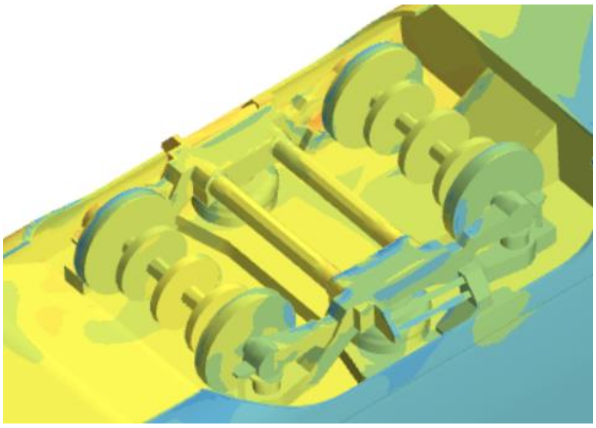
4.2 Surface pressure characteristics of high-speed train bogies under cross wind conditions

In order to study the bogie surface pressure distribution when the train runs under cross wind conditions, Figure 5 shows the bogie surface pressure distribution diagram when the train runs at 350km/h and the wind speed is 32.6m/s.

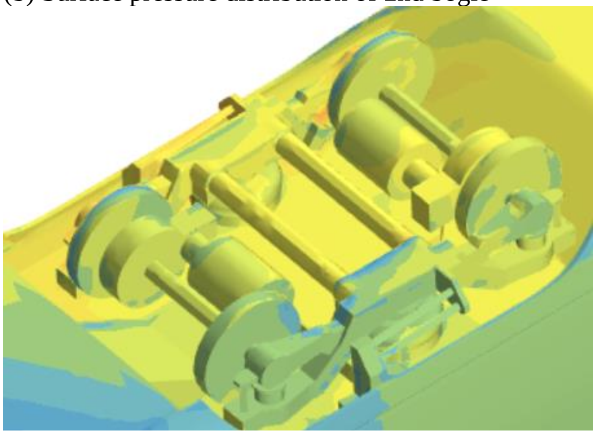
As can be seen from the figure, the windward side of the bogie is dominated by positive pressure, while the leeward side is dominated by negative pressure.



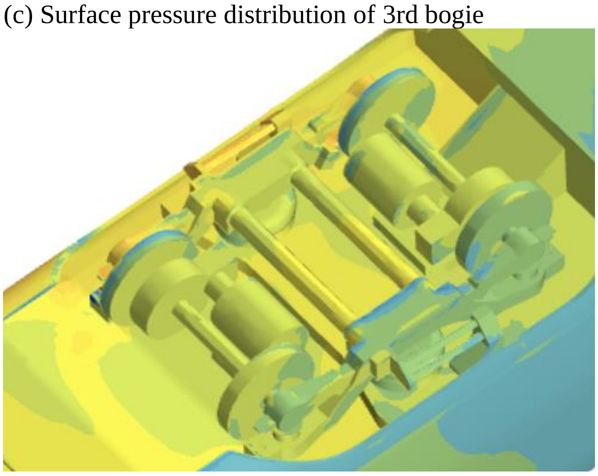
(a) Surface pressure distribution of 1st bogie



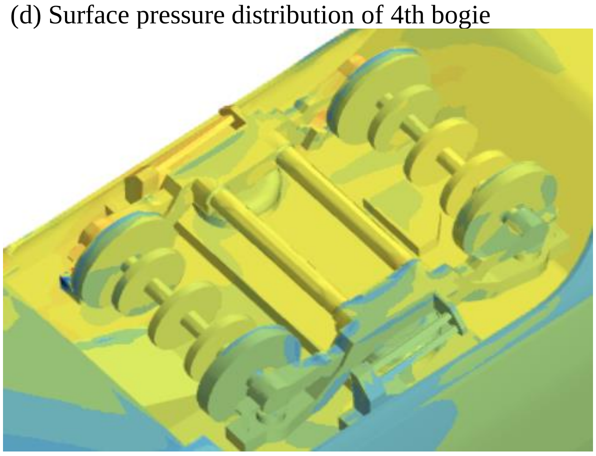
(b) Surface pressure distribution of 2nd bogie



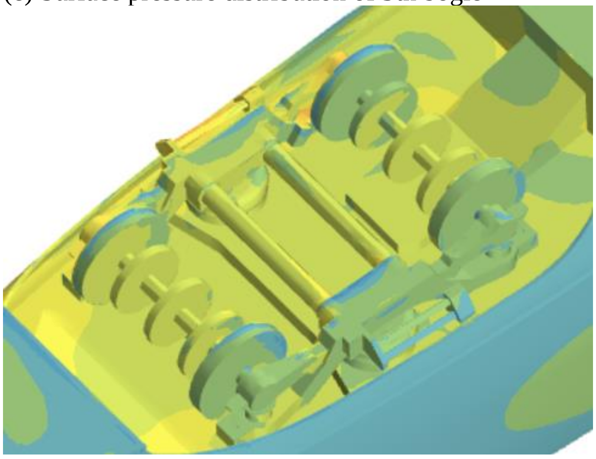
(c) Surface pressure distribution of 3rd bogie



(d) Surface pressure distribution of 4th bogie



(e) Surface pressure distribution of 5th bogie



(f) Surface pressure distribution of 6th bogie

Figure 5.Bogie surface pressure distribution

In order to study the spatial distribution of bogie surface pressure, Figure 6 shows the comparison of the maximum pressure at various measurement points at different positions of the bogie when the cross wind speed is 32.6m/s.

The data in the figure further indicates that the pressure on the windward side of the bogie wheel is positive pressure, while the leeward side is negative pressure. In the windward measurement points, the maximum pressure appeared at the 1st axle of the 1st bogie, and the pressure value was 818.88Pa; In each measuring point on the lee side, the maximum negative pressure appeared at the 2nd axle of the 1st bogie, and the pressure value was -579.88Pa. In addition, it can be seen from the data in the figure that the pressure values of the windward measurement points are not much different. The pressure values of the leeward measurement points are not much different except the negative pressure value of the 1st bogie 2nd measurement point, which indicates that the influence of wind on the pressure distribution of the bogie surface of the train is far greater than that of the train wind when the train runs on the open line under cross wind conditions.

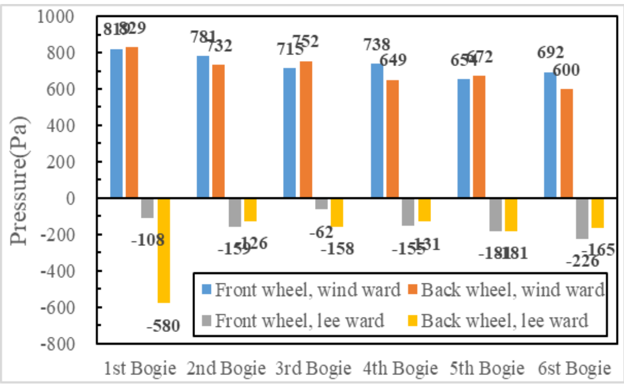


Figure 6. Comparison of the maximum pressure at the measuring point of bogie

4.3 Study on the influence of wind speed on body surface pressure

Figure 7 shows the relationship between the surface pressure of each measuring point of the body and the cross-wind speed of a single train running at a speed of 350km/h.

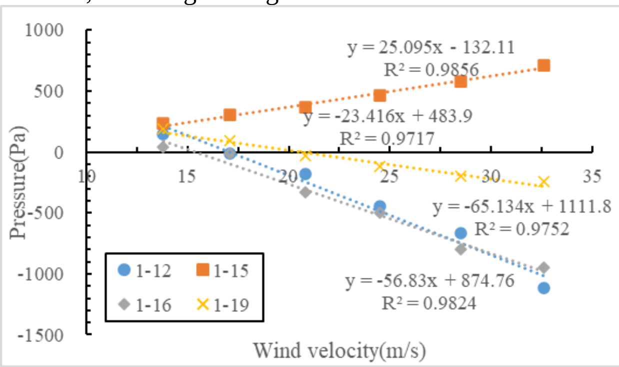
As can be seen from the figure, the pressure values of measuring points 1-15, 2-13 and 3-13 all increase with the increase of wind speed, and the two have a linear relationship. It can be seen from the arrangement of measuring points that the three measuring points are all located at the lower part of the center of the car body on the windward side, and the height of the measuring points is the same. It can be seen that when the train runs at a speed of 350km/h, the pressure value of the three vehicles in this area increases linearly with the increase of the wind speed.

Measuring points 1-19, 2-17 and 3-19 are located on the lee side, and their positions correspond to measuring points 1-15, 2-13 and 3-13. As can be seen from the figure, when the wind speed is low, the pressure value is positive. As the wind speed increases, the pressure value decreases in a linear relationship and gradually decreases to a negative value, indicating that with the gradual increase of the wind speed, the pressure value will be reduced to a negative value. The influence of wind on the surface pressure of the leeward side of the vehicle gradually exceeds that of the train wind.

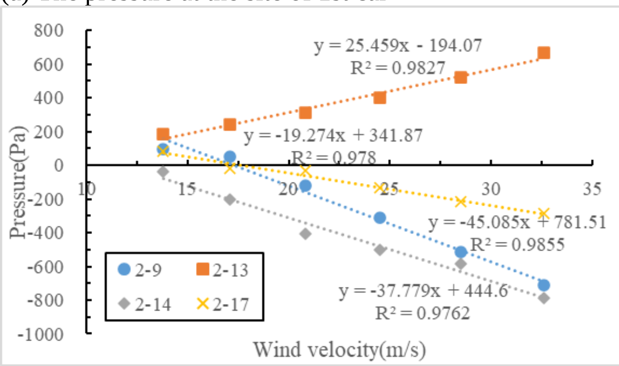
Measuring points 1-12 and 3-10 are located in the central position of the roof, and measuring points 1-16, 2-9, 2-14 and 3-9 are located at both ends of the roof. When the wind is about level 7, the surface pressure of the roof is close to 0, indicating that the influence of cross wind on the surface pressure of the roof is equivalent to that of the train wind. With the gradual increase of wind speed, the surface pressure of each measuring point on the roof decreases in a linear relationship and becomes negative pressure.

Measuring points 1-9 are located at the tip of the nose of the 1st car, points 1-11 are located at the junction of the streamlined front of the 1st car roof and the straight body of the 3rd car, points 3-16 are located at the nose tip of the 3rd car, and points 3-14 are located at the junction of the streamlined front of the 3rd car roof and the straight body of the 3rd car. As can be seen from the figure, the pressure value of each measuring point decreases in a linear relationship with the increase of wind speed. The reason why the pressure value of the measuring point at the streamlined locomotive gradually decreases with the increase of the wind speed is that when the wind speed is small, the main reason that affects the surface pressure of the train is the train running speed. When the wind speed gradually increases, the influence of the wind speed on the surface pressure of the streamlined locomotive is gradually greater than the train running speed. When the wind speed reaches a certain value, the influence of the wind speed on the body surface pressure and the influence of the train running speed on the body surface pressure cancel each other. In this case, the pressure value of the measuring point is 0. When the train runs at a speed of 350km/h, the wind speed of measuring points 1-9 reaching this equilibrium is about 22.5m/s. The wind speed of measuring points 1-11 and 3-16 reaching this equilibrium is about 17m/s, and the wind speed value of measuring points 3-14 reaching this equilibrium should be below 17.1m/s.

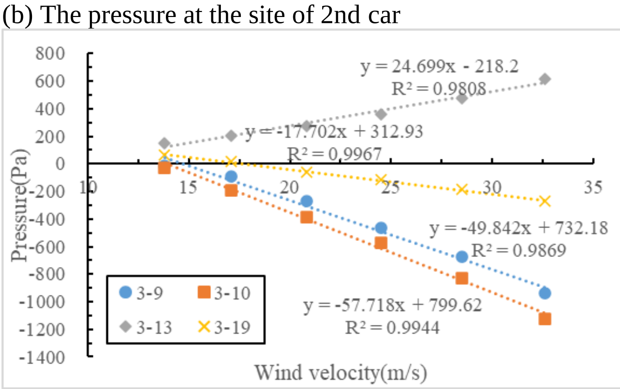
The pressure growth gradient of each measuring point is different. For measuring points 1-9, when the wind speed is 17.1m/s, 20.8m/s, 24.5m/s, 28.5m/ s and 32.6m/s, The pressure is reduced by 22.16%, 61.96%, 115.42%, 194.45% and 293.59%, respectively, compared with 13.8m/s, and the growth gradient is about -40.3.



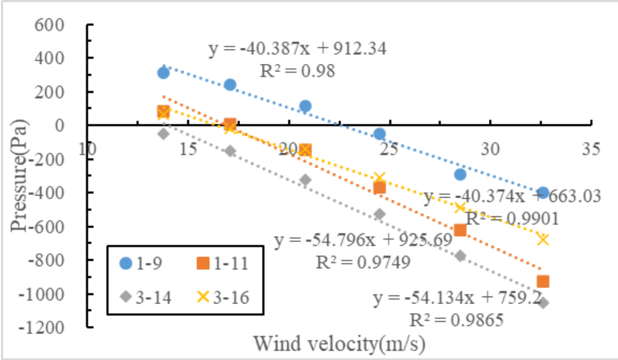
(a) The pressure at the site of 1st car



(b) The pressure at the site of 2nd car



(c) The pressure at the site of 3rd car



(d) The pressure of streamlined sections

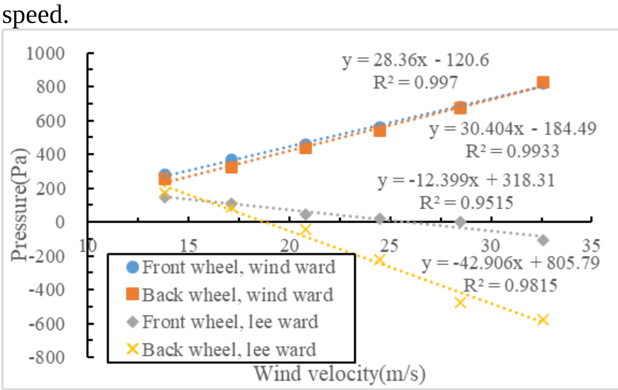
Figure 7. Variation curve of body pressure at measuring point with wind speed

4.4 Study on the influence of wind speed on bogie surface pressure

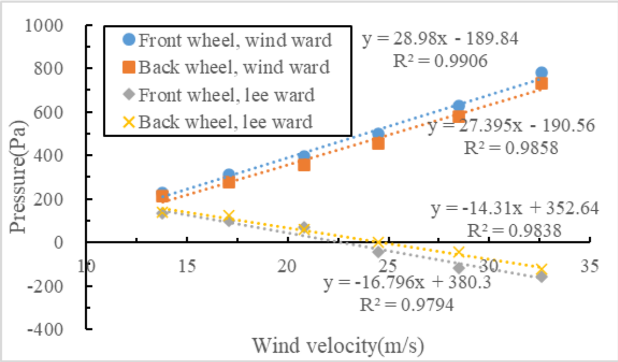
Figure 8 shows the variation curve of surface pressure of each bogie measuring point with wind speed when a single train runs at 350km/h.

It can be seen from the figure that no matter on which bogie, the pressure at the windward side measuring point always increases with the increase of wind speed, and the two have a linear relationship. The pressure of the measuring point on the lee side always decreases with the increase of wind speed, and the relationship between the two is linear. The pressure at the same position on the bogie increases with the increase of wind speed, and the two have a square relationship.

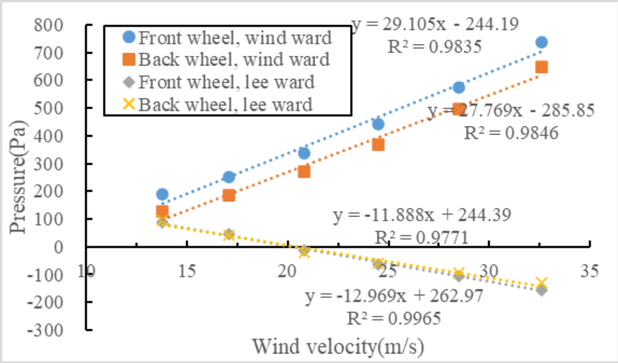
The pressure growth gradient of the measuring points on the windward side of bogies was about 28 Pa/(m/s). Except the measuring points on the leeward side of the rear axle of 1st bogie, the pressure growth gradient of the measuring points on the leeward side was about -12~-11. The pressure on the leeward side of the rear axle of 1st bogie reached -42.9 with the increase gradient of wind speed.



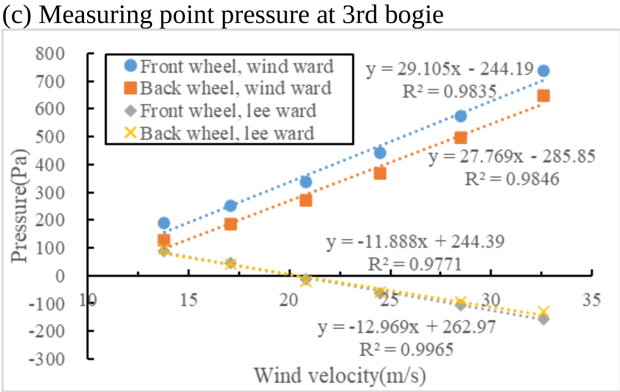
(a) Measuring point pressure at 1st bogie



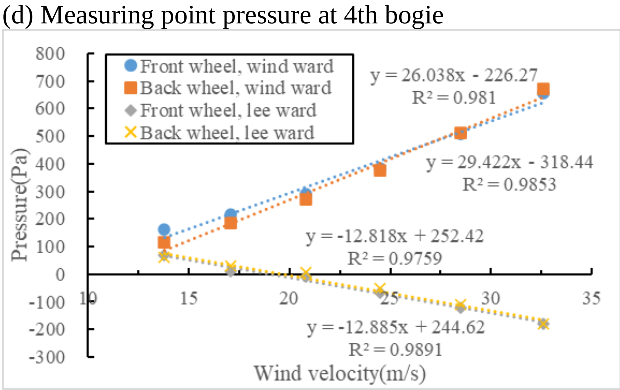
(b) Measuring point pressure at 2nd bogie



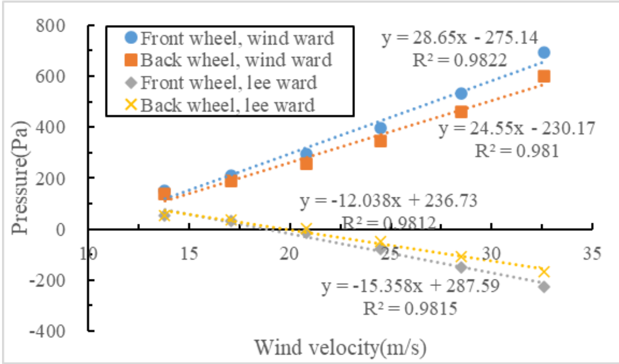
(c) Measuring point pressure at 3rd bogie



(d) Measuring point pressure at 4th bogie



(e) Measuring point pressure at 5th bogie



(f) Measuring point pressure at 6th bogie

Figure 8. Variation curve of bogie measuring point pressure with cross wind speed

5. Aerodynamic study on bogies of high-speed trains under cross wind conditions

5.1 Research on aerodynamic characteristics of high-speed train body under cross wind

Figure 9 shows the aerodynamic comparison of a single train body when it runs at 350km/h under the condition of a cross wind speed of 32.6m/s. As can be seen from the figure, the maximum values of resistance, side force and lift all appear in car 1, and the aerodynamic forces are 6149.15N, 38601.72N and 59931.51N respectively.

The minimum value of resistance appears on the 2nd car, which is 554.53N, and the resistance value of each car is quite different, and the maximum value is about 11.1 times of the minimum value.

The minimum value of lateral force appears on the 3rd car, and the difference between the lateral force values of each car is small, and the maximum value is about 1.32 times of the minimum value.

The minimum value of lift appears on the 3rd car, and the lift value of each car has little difference, and the maximum value is about 1.096 times of the minimum value.

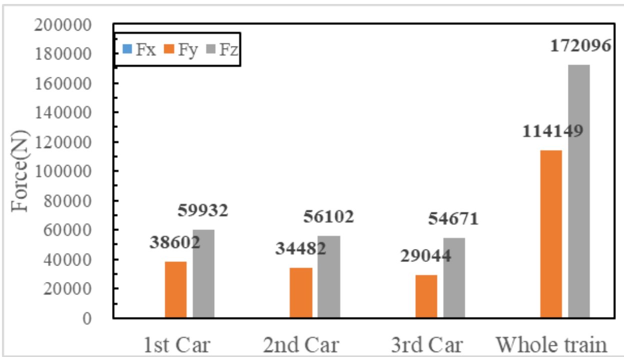


Figure 9.Aerodynamic comparison of vehicle body

5.2 Research on aerodynamic characteristics of high-speed train bogies under cross wind

Figure 10 shows the aerodynamic comparison of the bogies of a single train running at 350km/h under a wind speed of 32.6m/s.

As can be seen from the figure, there is little difference in the resistance values of bogies. The maximum resistance appears on the 3rd bogie and the minimum resistance appears on the 6th bogie, with a difference of about 180.48N. The total resistance contributed by the six bogies to the vehicle is about 577.06N, accounting for 4.5% of the vehicle resistance. It can be seen that the existence of bogies has little contribution to the vehicle resistance.

The difference in lateral force of bogies was also small, with the maximum appearing on 2nd bogie and the minimum appearing on 6th bogie, with a difference of about 236.84N. The total lateral force contributed by the six bogies to the vehicle is about 9999.26N, accounting for 8.76% of the lateral force of the vehicle. The side force is slightly reduced by the presence of the bogie.

The lift forces of each bogie differed greatly, with the maximum appearing at 5th bogie and the minimum appearing at 6th bogie, with the maximum being about 10.47 times of the minimum, and the difference being about 368.03N. The total lift contribution of the six bogies to the vehicle is about -1014.92N, accounting for 0.59% of the lateral force of the vehicle. It can be seen that the presence of bogies has little contribution to the lift of the vehicle.

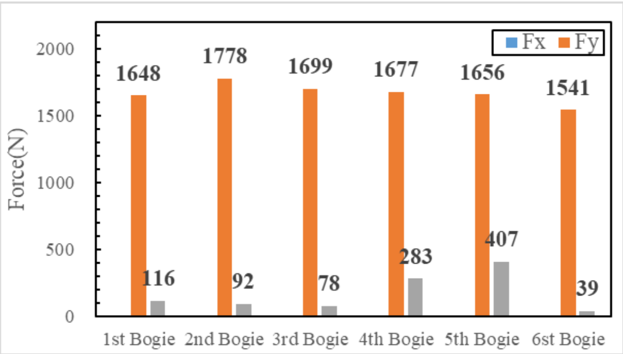


Figure 10.Aerodynamic comparison of bogies

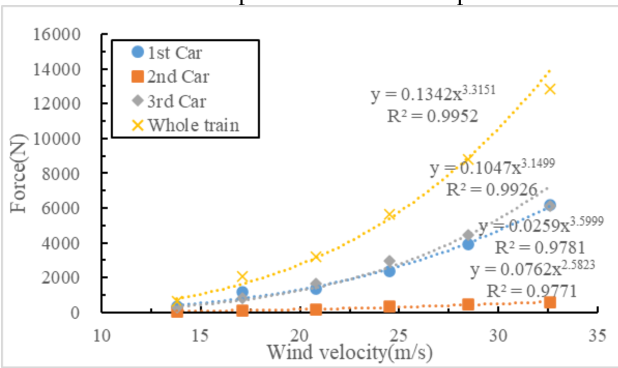
5.3 Study on the influence of wind speed on the aerodynamic force of high-speed train body

Figure 11 shows the relationship between the aerodynamic force of a single train body and the cross-wind speed when it runs at 350km/h.

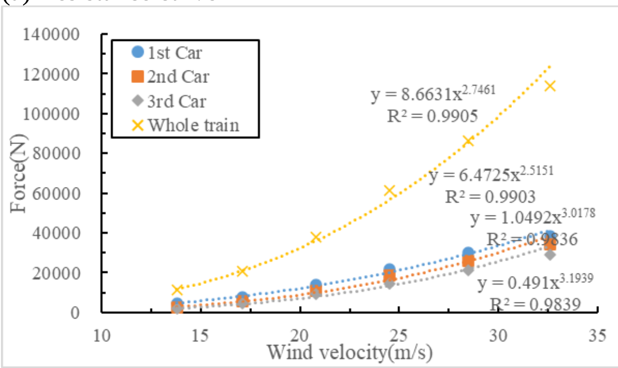
It can be seen that the resistance, side force and lift force of the same carriage increase with the increase of wind speed. With the gradual increase of wind speed, the resistance growth gradient of the 3rd car is the largest, increasing with an exponential relation of about 3.6. The resistance growth gradient of 2nd car is the smallest and increases with the exponential relation of 2.58. The resistance of 1st car is about 3.15 power to the wind speed. The relationship between vehicle resistance and wind speed is raised to the power of 3.32.

With the gradual increase of wind speed, the lateral force also gradually increased, and the growth gradient of each vehicle was little different, in order of 2.51, 3.02, 3.19. The relationship between the lateral force of the vehicle and the wind speed is raised to the power of 2.75.

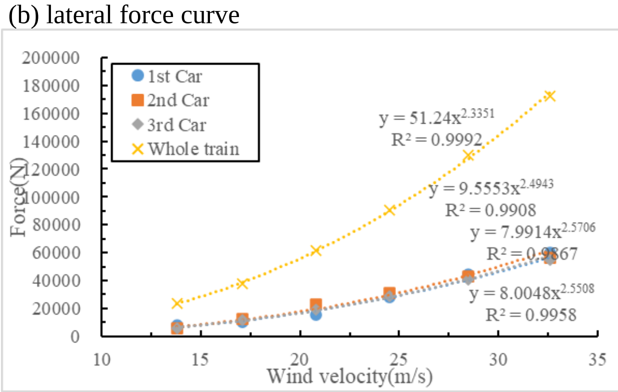
With the gradual increase of wind speed, the lift also shows a gradual increase trend, and the lift of each vehicle has little difference with the growth gradient of wind speed, which is about 2.5. The relationship between vehicle lift and wind speed is raised to the power of 2.3.



(a) Resistance curve



(b) lateral force curve



(c) Liftcurve

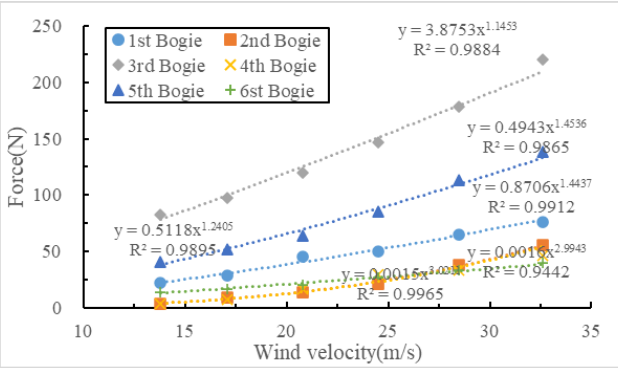
Figure 11.Variation curve of vehicle body aerodynamic force with cross wind speed

5.4 Study on the influence of wind speed on the aerodynamics of bogies of high-speed trains

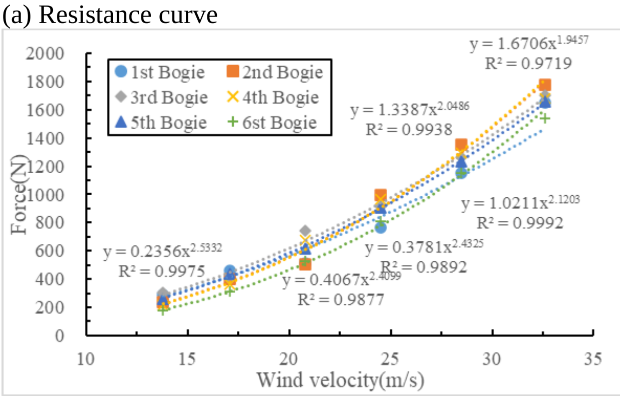
Figure 12 shows the relationship between the aerodynamic force of the bogie and the cross-wind speed when a single train runs at 350km/h.

As can be seen from the figure, the resistance and lateral force of the same bogie both increase with the increase of wind speed, and show a certain change law, in which the relationship between bogie resistance and wind speed is about 1.5 power, while the relationship between lateral force and wind speed is about 2 power.

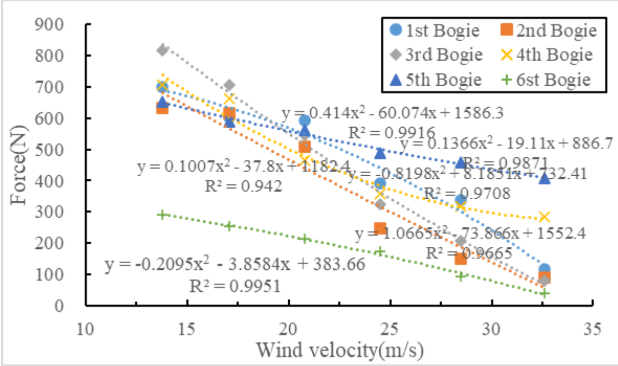
After the wind speed increases, the aerodynamic lift of the bogies gradually decreases, and the change law of each bogie is not the same. It can be seen that, affected by the geometric shape of the train, the lift of the bogies at different positions shows different changing trends after the wind speed increases. In addition, it should be noted that, as shown in Figure 12, the lift force of each vehicle or vehicle increases with the increase of wind speed, while the aerodynamic lift force of the bogie gradually decreases with the increase of wind speed. Thus, it can be seen that other positions of the vehicle body lead to the increase of the aerodynamic lift force of each vehicle or vehicle.



(a) Resistance curve



(b) lateral force curve



(c) Liftcurve

Figure 12. Variation curve of bogie aerodynamic force with cross wind speed

6.Research on aerodynamic torque of high-speed train bogies under cross wind conditions

6.1 Research on aerodynamic torque characteristics of high-speed train body under cross wind

Figure 13 shows the comparison of aerodynamic torque of each car of a single train running at 350km/h under the condition of a wind speed of 32.6m/s.

As can be seen from the figure, the maximum value of Mx, My and Mz appears in car 1, car 2 and car 3, respectively. The maximum value of Mx is 13605.52Nm, the maximum value of My is 12856.08Nm, and the maximum value of Mz is 42009.19Nm. The Mx, My and Mz are 36986.68Nm, 150606.58Nm and 298081.77Nm, respectively.

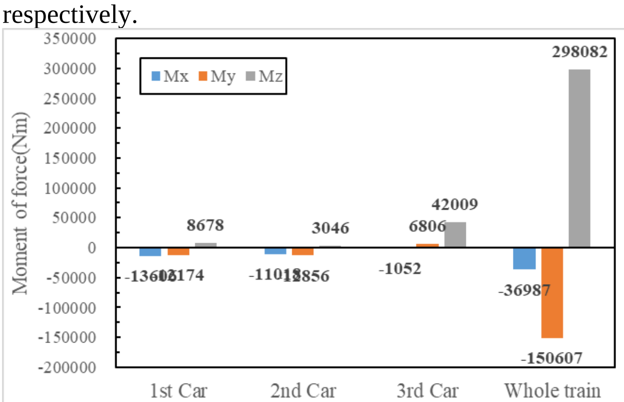


Figure 13. Comparison of aerodynamic torque of vehicle body

6.2 Research on aerodynamic torque characteristics of high-speed train bogies under cross wind

Figure 14 shows the comparison of the aerodynamic torque of the bogie when a single train runs at 350km/h under the condition of wind speed of 32.6m/s.

As can be seen from the figure, the maximum value of Mx and My both appeared at 4th bogie, and the aerodynamic torque was 1524.29Nm and 477.01Nm, respectively. The maximum Mz value occurs at 5th bogie, and the corresponding aerodynamic torque value is -203.78Nm.

In terms of Mx, the Mx direction of each car is opposite to the Mx direction of each bogie, indicating that when the high-speed train runs at 350km/h in a force 12 wind, the bogie cancels out the Mx of the car body. The 2nd car had the highest cancellation rate of about 25.9%.

In My aspect, the direction of My of each car is different from that of each bogie. The direction of My of the 1st car and the 3rd car is the same, the direction of My of the 3rd bogie is the same as that of the 2nd car, but the direction of 4th bogie My is opposite to that of the 2nd car. It can be seen that some bogies have a counteracting effect on the My of the vehicle.

On the Mz side, all bogies except 2nd bogie and 4th bogie are oriented in the same direction as the vehicle.

The share rate of the bogie for the complete vehicle Mx is about 22.27%, the contribution of My is about 0.58%, and the contribution of Mz is about 0.11%. It can be seen that when the train runs in a cross wind environment, the presence of bogies mainly has a greater impact on Mx, and a lesser impact on My and Mz.

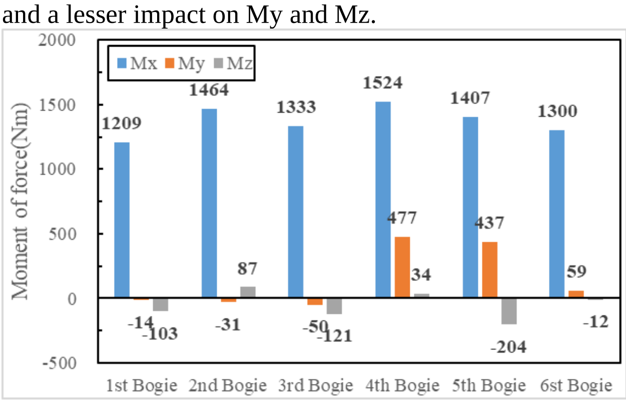


Figure 14. Comparison of aerodynamic torque of bogie

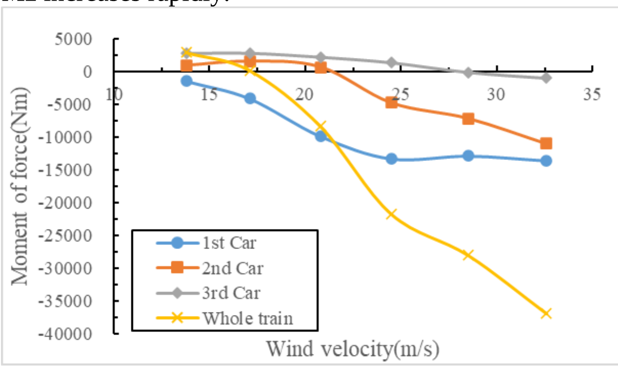
6.3 Effect of wind speed on aerodynamic torque of high-speed train body

Figure 15 shows the relationship between the aerodynamic torque of a single train body and the wind speed when it runs at 350km/h. As can be seen from the figure, the change of aerodynamic torque does not show a regular change with the increase of wind speed.

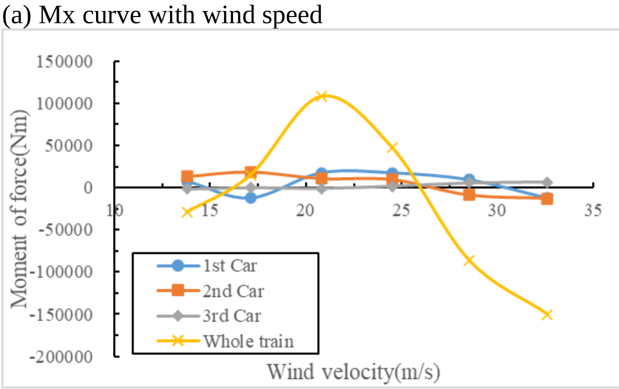
In terms of Mx, when the wind speed is small, the train wind is the main influencing factor of Mx. When the wind speed keeps increasing, the influence of wind on Mx gradually increases, so that the direction of Mx changes. When the wind speed is around 17m/s, the effect of wind and train wind on Mx is balanced. When the high-speed train is running at 350km/h, the wind level of the 1st car and the train wind to reach the balance of Mx wind level should be below 7, the 2nd car to reach the balance wind level should be slightly higher than 9, and the 3rd car to reach the balance wind level 11.

The increase of wind speed did not have a great impact on My. The direction of Y-axis is perpendicular to the body of the train and the opposite of the wind speed, so the wind speed will not have a great impact on My, and the calculation results are consistent with the actual situation.

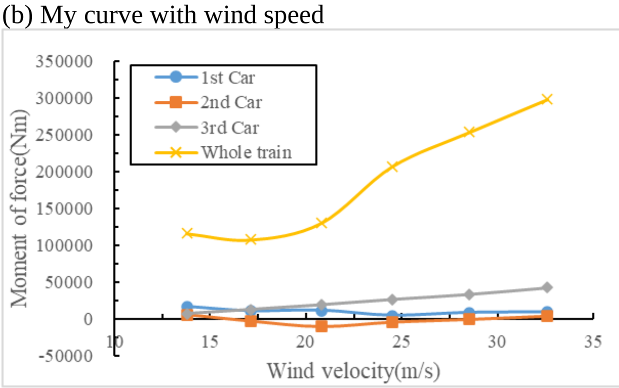
Mz showed a tendency to increase gradually with the increase of wind speed. From the Mz change curve of the vehicle, when the wind level is lower than 8, the Mz generated by the wind can offset the Mz generated by the train wind, but when the wind level is higher than 8, the Mz increases rapidly.



(a) Mx curve with wind speed



(b) My curve with wind speed



(c) Mz curve with wind speed

Figure 15. Aerodynamic torque curve of car body varies with cross wind speed

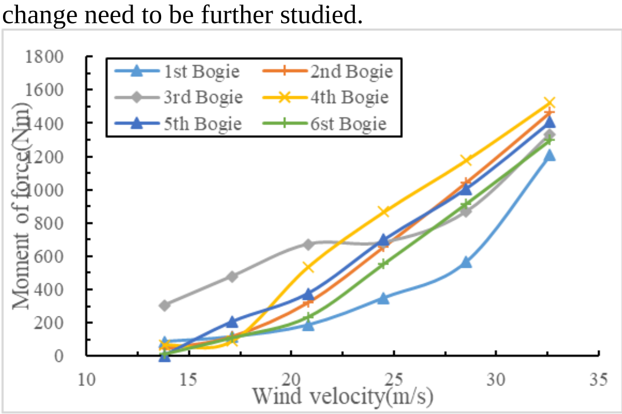
6.4 Effect of wind speed on aerodynamic torque of bogie of high-speed train

Figure 16shows the relationship between the aerodynamic torque of the bogie and the wind speed when a single train runs at 350km/h.

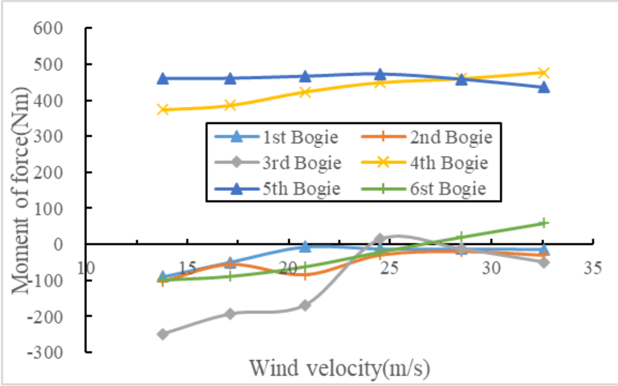
As can be seen from the figure, the Mx of all bogies increases with the increase of wind speed, and the growth gradient is large. Compared with Figure 16, it is found that the variation trend of bogie Mx is opposite to that of the whole vehicle. It can be seen that the direction of Mx at the position of the bogie is opposite to that of the whole vehicle. However, due to the low Mx value of the position of the bogie, it cannot have a great impact on the whole vehicle. Bogies and other devices that cause abrupt changes in the profile geometry of high-speed trains may be the reason why the Mx does not exhibit regular changes.

The direction of My at 4th bogie and 5th bogie is opposite to the other bogies, and it can be found that the increase in wind speed has little effect on the bogies My. This phenomenon is the same as the change law of the vehicle My, and the main reason for this phenomenon is precisely because the direction of the wind speed is the same as the direction of the Y axis.

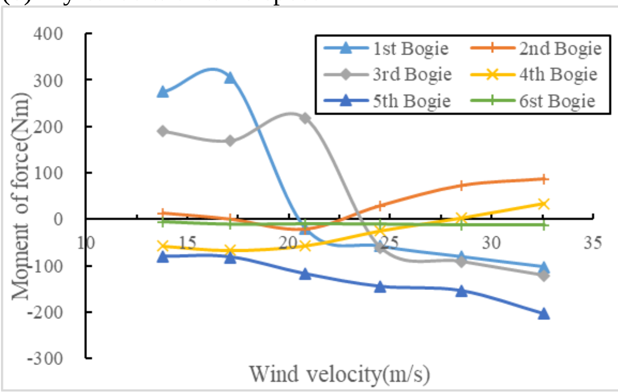
At low wind speeds, the Mz values produced at 1st bogie and 3rd bogie differed significantly from those of other bogies. The 1st bogie dropped sharply when the wind speed was about 17m/s, and the 3rd bogie showed the same trend, but the wind speed was about 22m/s. With the increase of wind speed, the Mz values of 1st bogie, 3rd bogie and 5th bogie gradually decreased with the increase of wind speed, while the Mz values of 2nd bogie, 4th bogie and 6th bogie gradually increased. In addition, it can be seen that except for 1st bogie and 3rd bogie, the curve trend of other bogies also changes when the wind speed is about 20m/s, and the reasons for this trend change need to be further studied.



(a) Mx curve with wind speed



(b) My curve with wind speed



(c) Mz curve with wind speed

Figure 16. Variation curve of bogie aerodynamic torque with cross wind speed

7. Conclusion

(1) The body surface pressure on the windward side of the train is mainly positive pressure, while the body surface pressure on the roof and leeward side is mainly negative pressure. The windward pressure of vehicle body increases linearly with the increase of wind speed, and the surface pressure of roof and leeward side decreases linearly with the increase of wind speed.

(2) The windward side of the bogie is dominated by positive pressure, while the leeward side is dominated by negative pressure. The surface pressure on the windward side of the bogie increases with the increase of wind speed, and the two have a linear relationship. The surface pressure of the lee side decreases with the increase of wind speed, and the relationship between the two is linear.

(3) The maximum resistance, side force, and lift of 1st car, and the resistance, side force, and lift of the same vehicle increase with the increase of wind speed, and the growth ratio is 2 to 3 powers.

(4) The maximum values of drag, lateral force and lift do not occur on the same bogie. The resistance and lateral force of the same bogie increase with the increase of wind speed, and show a certain change law, in which the relationship between bogie resistance and wind speed is about 1.5 power, and the relationship between lateral force and wind speed is about 2 power. The lift of bogie decreases with the increase of wind speed.

(5) The maximum values of Mx, My and Mz do not appear on the same vehicle. When the wind speed is small, the train wind is the main influencing factor of Mx. When the wind speed keeps increasing, the influence of wind on Mx gradually increases, so that the direction of Mx changes. From the Mz change curve of the vehicle, when the wind level is lower than 8, the Mz generated by the wind can offset the Mz generated by the train wind, but when the wind level is higher than 8, the Mz increases rapidly. The change of wind speed has little effect on the vehicle My.

(6) The maximum value of Mx and My both appeared at 4th bogie, and the maximum value of Mz appeared at 5th bogie. The Mx increases with the increase of wind speed, and the growth gradient is large. The change of wind speed has little effect on the bogie My.

Acknowledgements

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