World Journal of Engineering Research
Print ISSN: 2959-9865
Online ISSN: 2959-9873
DOI: https://doi.org/10.61784/wjer3052

DYNAMIC SIMULATION AND ANALYSIS OF MIXER TRUCK DEVICE ROLLOVER

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Abstract: To verify the feasibility and rationality of the mixer truck device design and reduce the risk of rollover accidents, this study, based on the ADAMS multi-body dynamics software, conducts 3D modeling, simulation model simplification, multi-body dynamics modeling and simulation, and simulation result analysis for the mixer truck device, with a focus on exploring the dynamic characteristics under rollover conditions to provide theoretical support for device optimization; in the multi-body dynamics modeling and simulation stage, the ADAMS software is used to build a virtual prototype, where the 3D model is imported in STEP format, and the simulation results show that the dynamic characteristics of the mixer truck are consistent with the actual working conditions—during turning, the displacement in the X-direction is greater than that in the Z-direction with consistent curve trends, the velocities in the X and Z directions are the same, and the maximum total velocity is 1.6 m/s, while under the rollover condition, the displacement of the center of mass in the Y-direction is -5 mm at the initial moment and reaches 348.3 mm at the moment of rollover, the initial velocity is 0, reaches a maximum velocity of 2.1 m/s at 4 seconds and then decreases gradually, and the velocity of the center of mass in the Z-direction is the largest; through systematic multi-body dynamics simulation, this study clarifies the variation laws of displacement and velocity of the mixer truck under turning and rollover conditions, verifies the rationality of the device design, and provides data support and theoretical basis for the structural optimization of the mixer truck device and the prevention and control of rollover risks.
Keywords: Mixer truck device; Adams; Rollover conditions; Dynamic characteristics

1 INTRODUCTION

With the development of the new era, concrete mixer trucks are being used with increasing frequency. The rollover of concrete mixer trucks can cause severe damage to people's lives and property[1,2]. Therefore, verifying the feasibility and rationality of mixer truck device design is of great significance for reducing the risk of rollover accidents.Domestic experts and scholars have also conducted extensive research on the operating conditions of vehicles during cornering[3]. For example, Deng Yadong et al. established a multi-body dynamics simulation model of vehicles based on ADAMS software and analyzed the steering characteristics when a step input is applied to the vehicle's steering wheel angle. Researchers from Chang'an University, including Wei Lang, analyzed the process of vehicle rollover motion on the basis of establishing a three-dimensional vehicle dynamics model. Professor Yu Qiang from the same university has also conducted in-depth research on the issue of improving vehicle roll stability through active suspension systems.Studying the variation laws of displacement and velocity of mixer trucks under cornering and rollover conditions, and verifying the rationality of device design, provides important data support for the structural optimization of mixer truck devices and the prevention and control of rollover risks[4].

2 Theoretical Foundations of Multi-Body Dynamics

Multi-body dynamics refers to a discipline whose research object is a system composed of multiple rigid or flexible bodies interconnected through certain constraint relationships and performing relative motions. These constraints are usually non-holonomic constraints, scleronomic constraints, and rheonomic constraints. Based on classical mechanics, multi-body dynamics has gradually developed and possesses broad application value and prospects in the fields of mechanical kinematics and dynamics.Currently, multi-body dynamics has been integrated with modern computing technology, with its basic task being the derivation of mathematical models suitable for computer programming. Closely linked to the development of contemporary computer technology, it has gained widespread recognition internationally.According to whether flexible bodies are included in the model, multi-body dynamics can be divided into multi-rigid-body dynamics and multi-flexible-body dynamics[5]. When a motion system operates at a low translational or rotational speed, and the influence of external forces on its deformation is negligible, its simulation can be treated as a multi-rigid-body system. Conversely, it is necessary to model the main moving components of the system as flexible bodies. However, since the motion speed of this mechanism is relatively low, the dynamic simulation is performed based on the multi-rigid-body theory[6].

The coordinate transformation matrix between the centroid reference coordinate system of the mechanical system component and the ground coordinate system is given by Equation (1).

$$A^{\mathrm{gi}} = \begin{bmatrix} \cos\psi\cos\phi - \sin\psi\cos\theta\sin\phi & -\cos\psi\sin\phi - \sin\psi\cos\theta\cos\phi & \sin\psi\sin\theta \\ \sin\psi\cos\phi + \cos\psi\cos\theta\sin\phi & -\sin\psi\sin\phi + \cos\psi\cos\theta\cos\phi & -\cos\psi\sin\theta \\ \sin\theta\sin\phi & \sin\theta\cos\phi & \cos\theta \end{bmatrix} \tag{1}$$

Define an Euler rotation axis coordinate system, whose three unit vectors correspond to the axes of the three Euler rotations mentioned above; thus, the three axes are not mutually perpendicular[7]. The coordinate transformation matrix from this coordinate system to the component's centroid coordinate system is given by Equation (2).

$$B = \begin{bmatrix} \sin\theta\sin\phi & 0 & \cos\theta \\ \sin\theta\cos\phi & 0 & -\sin\theta \\ \cos\theta & 0 & 1 \end{bmatrix} \tag{2}$$

The angular velocity of the component is expressed as Equation (3).

$$\omega = B\dot{\gamma} \tag{3}$$

In ADAMS, the variables introduced are the components of angular velocity in the Euler rotation axis coordinate system as Equation (4).

$$\omega_e = \dot{\gamma} \tag{4}$$

Considering the constraint equations, the system's dynamic equations can be derived as follows using the energy form of Lagrange's first equation with Lagrange multipliers in ADAMS. Here, T represents the kinetic energy expressed in terms of the system's generalized coordinates, as given by Equation (5).

$$\frac{d}{dt}\left(\frac{\partial T}{\partial \dot{q}_j}\right) - \frac{\partial T}{\partial q_j} = Q_j + \sum_{i=1}^{n} \lambda_i \frac{\partial \phi}{\partial q_j} \tag{5}$$

In ADAMS, the generalized momentum is further introduced by Equation (6).

$$P_j = \frac{\partial T}{\partial \dot{q}_j} \tag{6}$$

Simplify the expression of the constraint reaction force as Equation (7).

$$C_j = \sum_{i=1}^{n} \lambda_i \frac{\partial \phi}{\partial q_j} \tag{7}$$

Thus, the equation is simplified to Equation (8).

$$\dot{P}_j - \frac{\partial T}{\partial q_j} = Q_j - C_j \tag{8}$$

The kinetic energy is further expressed as Equation (9).

$$T=\frac{1}{2}\dot{R}^{T}M\dot{R}+\frac{1}{2}\dot{\gamma}^{T}B^{T}JB\dot{\gamma} \tag{9}$$

Among them, M is the mass matrix of the component, and J is the inertia matrix of the component in the centroid coordinate system.

Express the following equation in terms of the translational direction and rotational direction respectively, as shown in Equations (10)-(12).

$$\dot{P}_R-\frac{\partial T}{\partial q_R}=Q_R-C_R \tag{10}$$

$$\dot{P}_\gamma-\frac{\partial T}{\partial q_\gamma}=Q_\gamma-C_\gamma \tag{11}$$

$$\dot{P}_R=\frac{d}{dt}\left(\frac{\partial T}{\partial \dot{q}_R}\right)=\frac{d}{dt}\left(M\dot{R}\right)=M\dot{V},\frac{\partial T}{\partial q_R}=0 \tag{12}$$

The equation is simplified to Equation (13)-(14).

$$M\dot{V}=Q_R-C_R \tag{13}$$

$$P_\gamma=\left(\frac{\partial T}{\partial \dot{q}_\gamma}\right)=B^{T}JB\dot{\gamma} \tag{14}$$

Matrix B contains Euler angles. To simplify the derivation, each component in ADAMS is thus assigned the following 12 variables as Equation (15)-(16).

$$\begin{aligned}
&V=\left[V_x,V_y,V_z\right]^T\\
&R=\left[x,y,z\right]^T\\
&P_\gamma=\left[P_\psi,P_\theta,P_\phi\right]\\
&\omega_e=\left[\omega_\psi,\omega_\theta,\omega_\phi\right]^T\\
&\gamma=\left[\psi,\theta,\phi\right]^T
\end{aligned} \tag{15}$$

$$\begin{aligned}
&M\dot{V}=Q_R-C_R\\
&V=\dot{R}\\
&\dot{P}_\gamma-\frac{\partial T}{\partial q_\gamma}=Q_\gamma-C_\gamma\\
&P_\gamma=B^{T}JB\omega_e\\
&\omega_e=\dot{\gamma}
\end{aligned} \tag{16}$$

By integrating the constraint equations, ADAMS can automatically establish the system's dynamic equations and differential-algebraic equations, thereby solving system dynamics as shown in Equations (17).

$$\begin{aligned} &\dot{P}-\frac{\partial T}{\partial q}+\phi_q^T\lambda+H^TF=0 \\ &P=\frac{\partial T}{\partial \dot{q}} \\ &u=\dot{q} \\ &\phi(q,t)=0 \\ &F=f(u,q,t) \end{aligned} \tag{17}$$

Among them, P is the generalized momentum of the system, and H is the coordinate transformation matrix of external forces.

3 Model Establishment

3.1 Three-Dimensional Solid Modeling of the Mixer Truck Device

Since the mixer truck device must bear the force of the load during operation and therefore needs to work stably and safely for a long time, it is necessary to ensure that it has sufficient strength and stiffness in the design process to avoid dangers caused by fractures due to insufficient strength[8]. The three-dimensional modeling steps are shown in Figure 1.

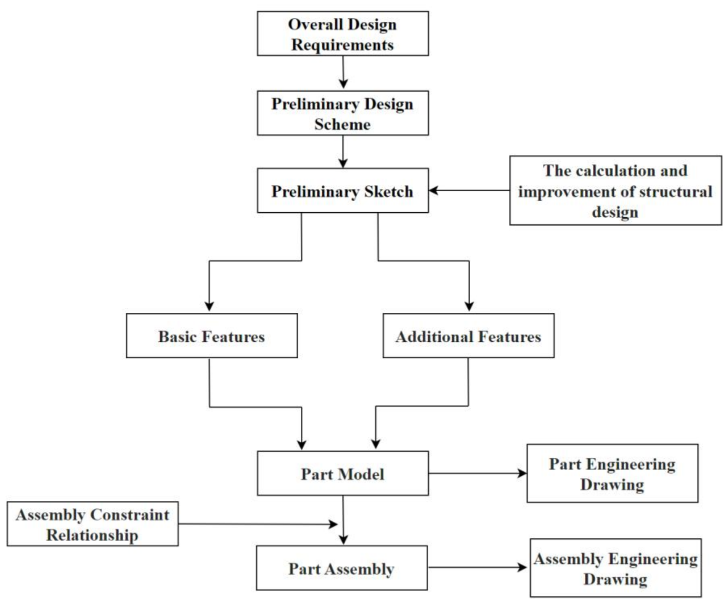


Figure 1 Three-Dimensional Modeling Steps

The three-dimensional simulation model of the mixer truck device is shown in Figure 2.

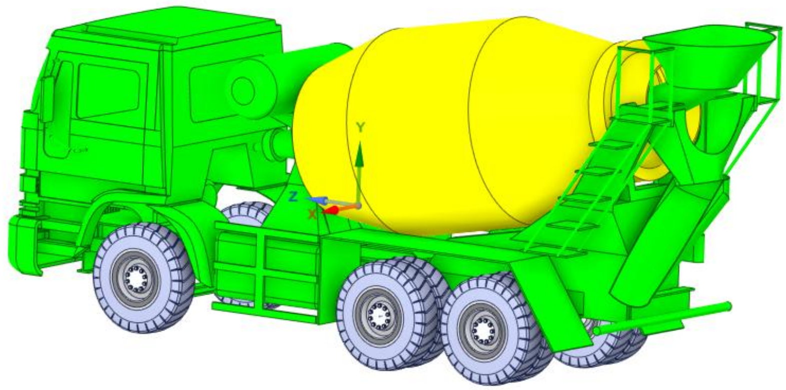


Figure 2 Three-Dimensional Simulation Model of the Mixer Truck Device

3.2 Model Import

First, save the mixer truck device as a Parasolid (*.x-t) or STEP file format, then import it into the ADAMS dynamic simulation software. When the mixer truck device model is imported into ADAMS 2020, there is only a relative positional relationship between its components. During simulation, various constraint pairs are manually added according to the actual motion state and constraint relationship, and marker points are automatically generated, as shown in Figure 3.

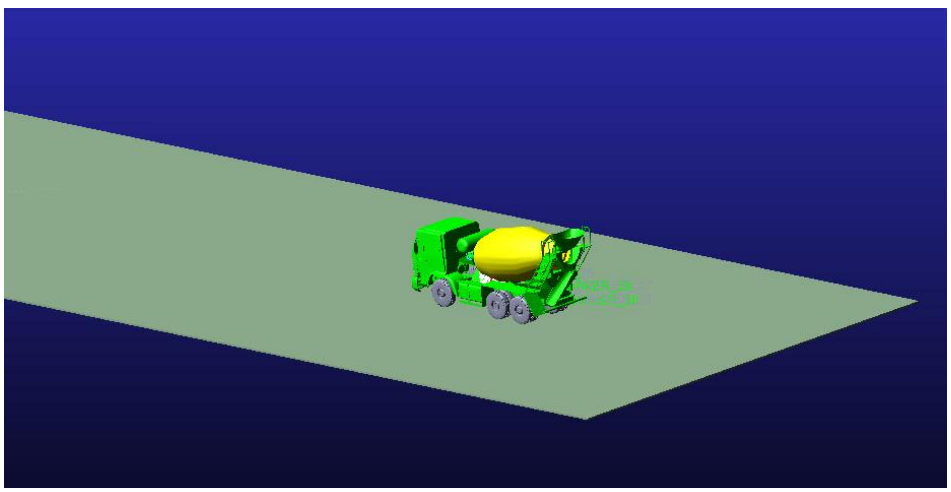
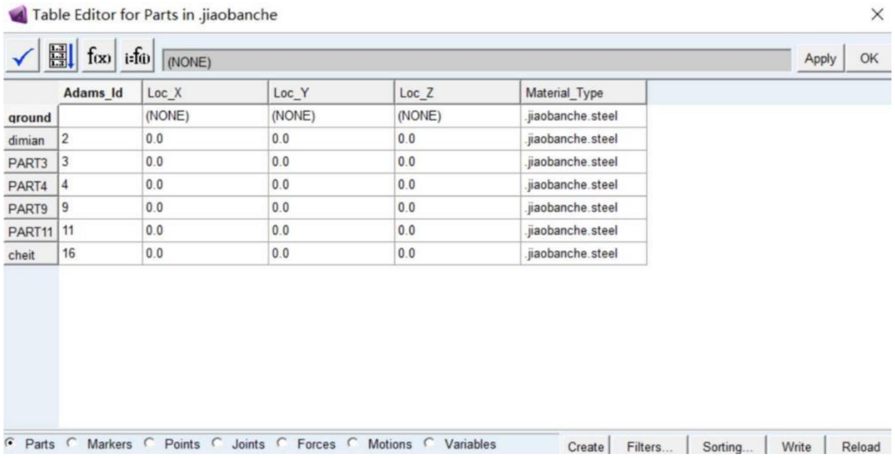


Figure 3 Dynamic Simulation Model of the Mixer Truck Device

3.3 Material Definition

Since the generation of dynamic effects in ADAMS relies on the mass properties of the model's components, it is necessary to define the material for each part of the model when conducting dynamic analysis. The software automatically calculates the mass of each component based on the material's density and volume, and finally generates dynamic effects according to the mass and gravitational acceleration. Newly imported models have no mass information, which needs to be defined and set manually by the user[9]. To modify and set the mass information, right-click on all components, and select "geometric shape and material type" as the mass definition method. After the settings are completed, the model can be verified to prevent missing the property settings of any component. The material definition of the mixer truck device parts is shown in Figure 4.



	Adams_Id	Loc_X	Loc_Y	Loc_Z	Material_Type
ground		(NONE)	(NONE)	(NONE)	.jiaobanche.steel
dimian	2	0.0	0.0	0.0	.jiaobanche.steel
PART3	3	0.0	0.0	0.0	.jiaobanche.steel
PART4	4	0.0	0.0	0.0	.jiaobanche.steel
PART9	9	0.0	0.0	0.0	.jiaobanche.steel
PART11	11	0.0	0.0	0.0	.jiaobanche.steel
cheit	16	0.0	0.0	0.0	.jiaobanche.steel

Figure 4 Material Definition of the Mixer Truck Device

3.4 Constraint Relationships of the Mixer Truck Device

When the mixer truck device model is imported into ADAMS software, there is only a relative positional relationship between its components, similar to objects floating in three-dimensional space. Each object has six degrees of freedom, namely three translational degrees of freedom along the positive direction of the spatial coordinate axes and three rotational degrees of freedom around the coordinate axes. If their mutual relationships are not defined, the simulation will fail due to insufficient degrees of freedom. Therefore, it is necessary to establish constraints for the relevant components of the model according to the working conditions. When constraints are established between components, marker points are automatically generated to determine the position of the constraint pairs, and these marker points are created along with the establishment of constraint relationships[10].

The quantity and type of each constraint pair of the mixer truck device are shown in Table 1.

Table 1 Quantity and Type of Each Constraint Pair of the Mixer Truck Device

Constraint Type	Number of Constraint Pairs	Number of Degrees of Freedom Restricted by Constraint Pairs
Revolute Joint	3	5
Fixed Joint	2	6

According to the working conditions of the mixer truck device, the constraint relationships after being added are shown in Figure 5 and Figure 6 below.

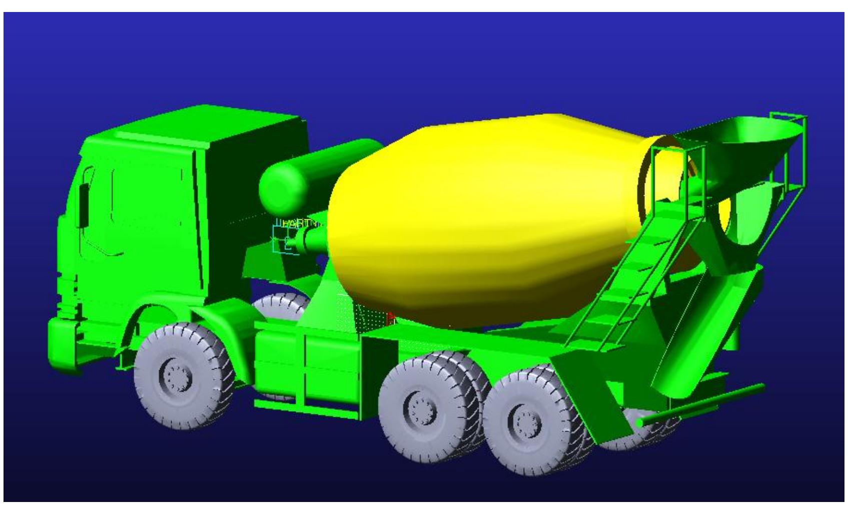


Figure 5 Three-Dimensional Model of Mixer Truck

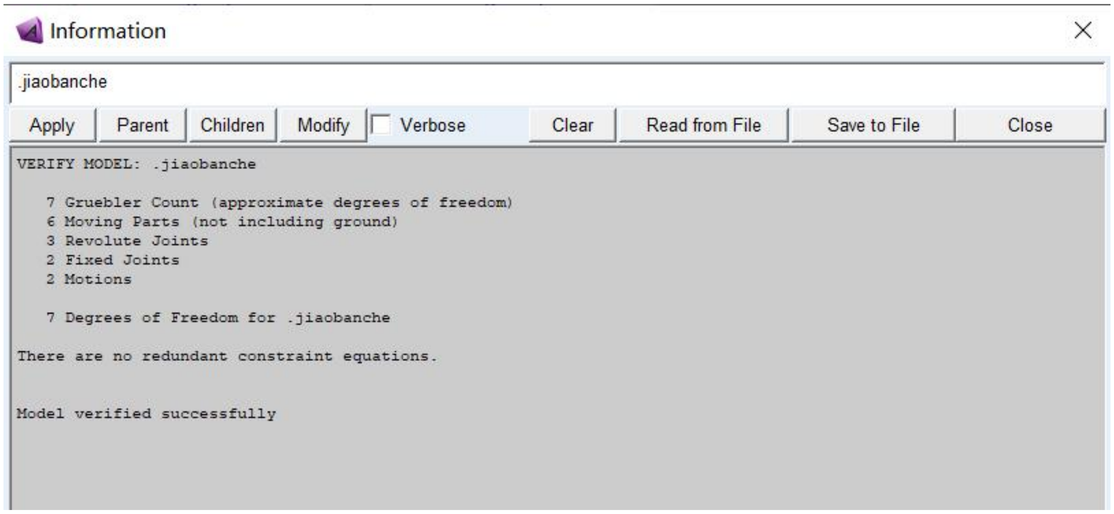


Figure 6 Constraint Relationships

3.5 Contact Relationships of the Mixer Truck Device

ADAMS uses Coulomb friction to calculate the frictional force between contacting parts, whose value is equal to the product of the impact normal force and the friction coefficient. When the relative motion velocity of two contacting objects is less than the static friction transition velocity v, the friction coefficient between them is taken as the static friction coefficient; when the relative motion velocity of the two contacting objects is greater than the dynamic friction transition velocity v, the friction coefficient between them is taken as the dynamic friction coefficient. Generally speaking, the dynamic friction coefficient and static friction coefficient are related to factors such as the material properties and surface roughness of the two contacting objects. The material properties are shown in Figure 7.

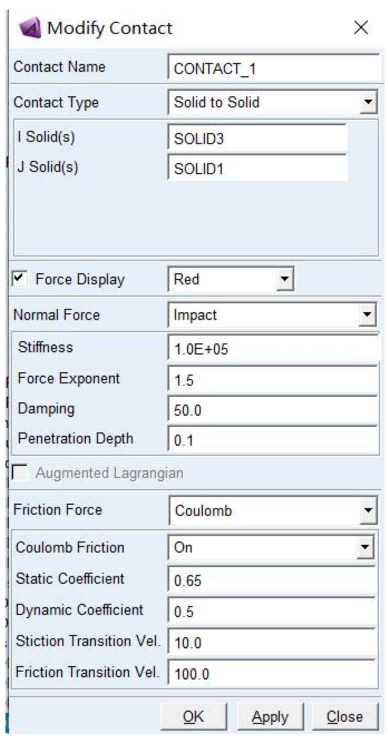


Figure 7 Material Properties

There are generally two types of drives: one is forward drive, and the other is inverse drive. Forward drive involves determining the motion of each rigid body in the system based on the known driving force applied to the rigid body system; while inverse drive involves calculating the force on each rigid body in the system based on the known motion of each rigid body. In this paper, when conducting simulation analysis on the mixer truck device, a velocity drive is adopted, as shown in Figure 8 below.

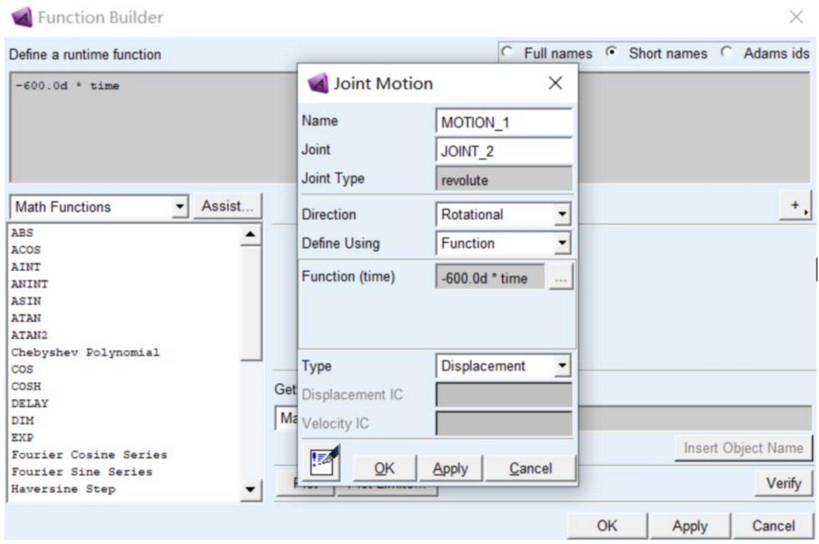


Figure 8 Velocity Drive Constraint

4 SIMULATION AND RESULT ANALYSIS

4.1 Simulation Setup

After completing the import of the mixer truck device model, unit definition, material property definition, constraint addition, and drive addition as above, the multi-body dynamics model of the mixer truck device has been fully established. Then, it is necessary to set the simulation analysis parameters, simulation time, and simulation steps, and finally perform the simulation calculation.

In terms of solver types, multi-body dynamics simulation analysis mainly has two forms: interactive simulation and scripted simulation. Scripted simulation is mainly used for multi-body systems where certain kinematic pairs, loads, drives, etc., need to be deactivated or activated at specific moments during motion. The simulation process requires scripting, which is relatively cumbersome to operate. Interactive simulation is the most commonly used simulation form, with fewer control parameters and simple operation, which can meet the simulation analysis needs of conventional multi-body systems. In summary, interactive simulation is adopted for the simulation analysis of the mixer truck device.

Interactive simulation mainly has two control parameters: simulation time and simulation steps. The simulation time is set to 5 seconds. Simulation steps have an important impact on the results of simulation analysis. Since ADAMS analysis results are generally curves of the kinematic and dynamic properties of each component, these curves are essentially composed of a series of discrete points solved by the software solver. Therefore, the number of simulation steps needs to match the simulation time. If the simulation time is long but the number of simulation steps is too small, although the simulation time can be reduced and the simulation efficiency improved, some point data may be missing, which affects the simulation accuracy. Conversely, increasing the number of simulation steps can effectively improve the accuracy of simulation results, but it will reduce the calculation efficiency of the entire multi-body system during simulation, and may even cause the computer to crash. Therefore, to ensure the accuracy of the simulation results while taking into account the simulation efficiency, the number of simulation steps is set to 1000. The step size is shown in Figure 9.

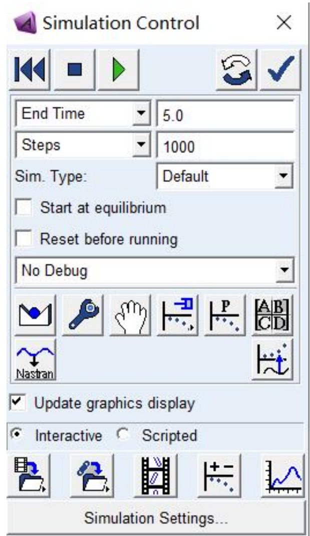


Figure 9 Simulation Step Size Setup

4.2 Simulation Result Analysis

Figures 10-12 show the variation curve of the centroid displacement in the y-direction when the mixer truck rolls over under the action of an external moment during a turn. It can be seen from the figures that at the initial moment, the displacement in the y-direction is -5 mm; at the instant when the mixer truck rolls over while turning, the displacement in the y-direction is 348.3 mm.This indicates that the center of mass has shifted significantly in the lateral direction, exceeding the range where the mixer truck can maintain stability, which is a key manifestation of the rollover. After the rollover occurs, the displacement of the center of mass in the Y-direction drops rapidly, reflecting the process of the center of mass falling back after the mixer truck completes the rollover, which is consistent with the actual situation.

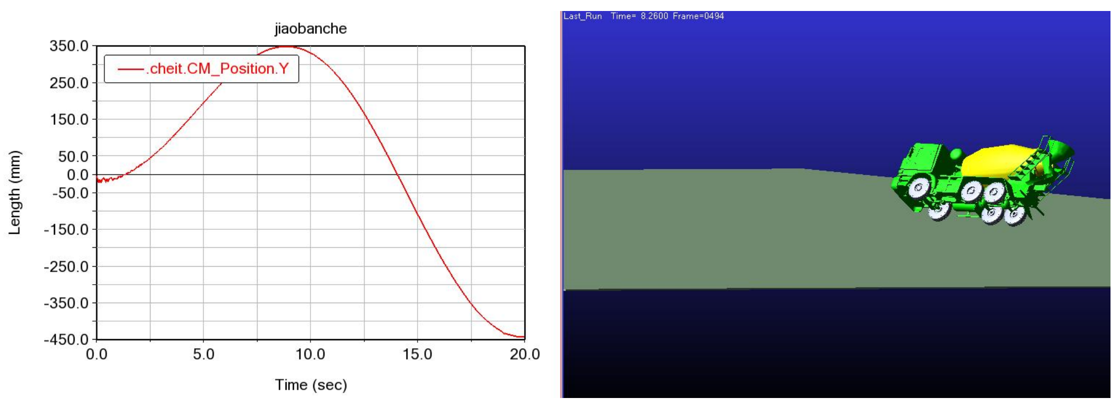


Figure 10 Centroid Displacement Diagram

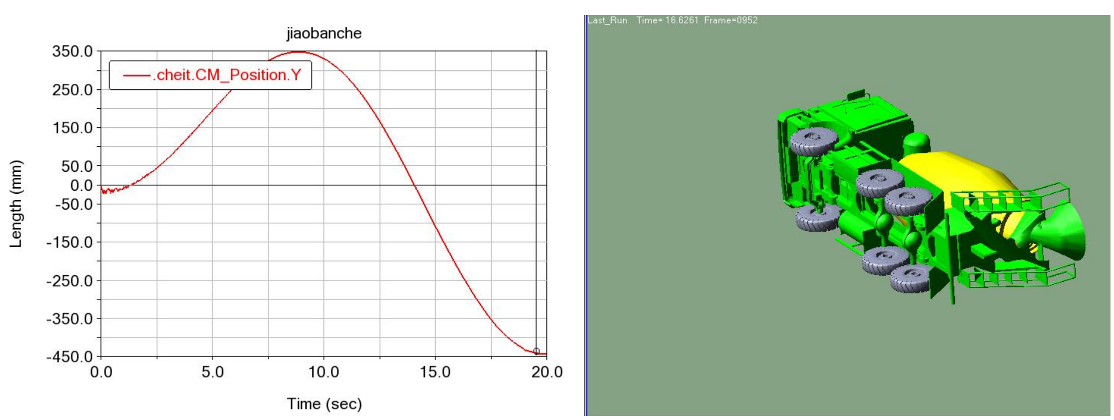


Figure 11 Centroid Displacement Diagram

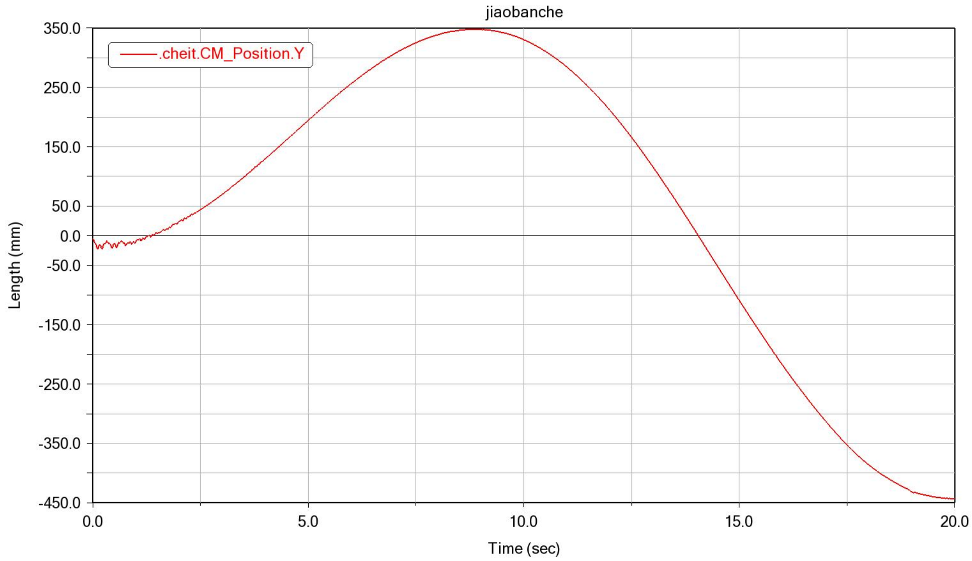


Figure 12 Centroid Displacement Diagram

In the initial stage, the velocity of the centroid of the mixer truck increases rapidly, which simulates the process of the mixer truck accelerating to the target driving speed before turning. After that, the velocity remains in a stable stage of about 2000 mm/s, simulating the mixer truck driving at a stable speed and entering the turning condition. When the rollover occurs, the velocity gradually decreases, reflecting the situation that the mixer truck's speed decreases due to factors such as impact during the rollover process.The velocity curves of the mixer truck when rolling over during a turn are shown in Figures 13-14.

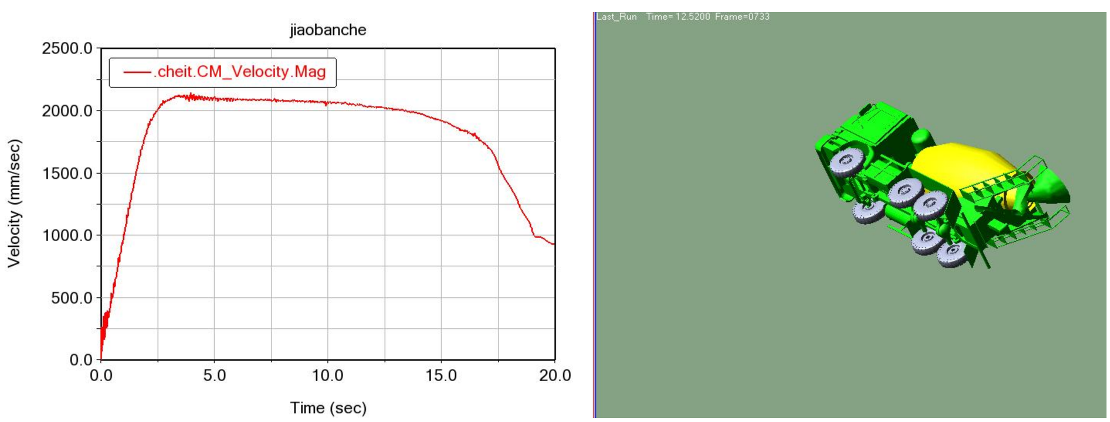


Figure 13 Velocity Curve Diagram

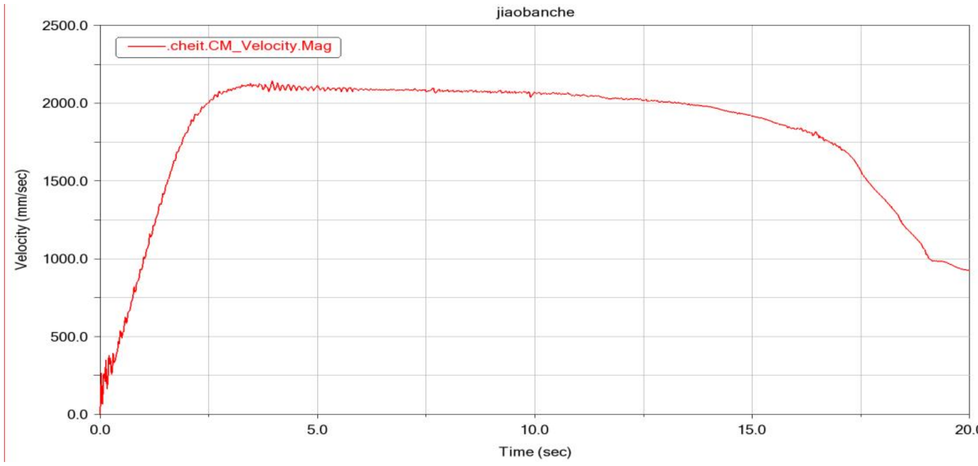


Figure 14 Velocity Curve Diagram

The overall fluctuation is small, indicating that the change in lateral speed is relatively insignificant during both normal driving and rollover. The rollover is mainly caused by excessive lateral displacement of the center of mass, rather than being dominated by a significant sudden change in lateral speed.

It rises initially, then remains stable, and decreases significantly after the rollover occurs. This reflects the change in the mixer truck's vertical movement state, with vertical movement affected during the rollover, which is consistent with the actual situation.

COMPETING INTERESTS

The authors have no relevant financial or non-financial interests to disclose.

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