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Study on System Dynamics of Long and Heavy-Haul Train

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The long and heavy-haul train transportation has already been recognized as the direction of railway freight development by the international society because of its remarkable economic benefits. But with increasing of train formation and hauling weight, the problems of safety in transportation have become prominent, such as destructive effect on railway line, braking failure, coupler failure and derailment, and so on, which become the bottleneck of heavy-haul train freight transportation healthy development. Accordingly, it is necessary to have an overall thorough research on the system dynamics of long and big train. Currently, most of the studies have focused on the longitudinal dynamics, but only a little study on the lateral and vertical dynamics. The main reason for it is that there are some difficulties in modeling of the long and big train. It can be described as follows:

(1) It is a very complicated and troublesome task to set up a complete train system model, and almost impossible to carry out the numerical simulation due to so many degrees of freedom (DOFs) of the whole train. Most of the foregone studies of train dynamics often focused on the longitudinal dynamics in order to simulate the operation of train and it often considered a little DOF. However, we should take almost all the important DOFs into the model of train when having a study on the lateral and vertical dynamics. With the increase of vehicle in a train, the DOF will be growth with geometric series, if all the DOFs of every vehicle has been considered, it will cause freedom degrees blast, and the computing matrix of model will also become enormous. Lastly, it is impossible to complete the dynamic calculation of train.

(2) It is inconvenience for modeling of long and big train and the universality is poor. The model of train dynamics should be modified with different train formations, so it is too complicated to be modeled, and the universality and flexibility of model are very poor.

It is impossible for us to make a system study on the train dynamics if the modeling problem can't be break through. Accordingly, we dance to another tune and put forward a new modeling method for the long and big train in this article: Modular Modeling Method Based on Circular-Variable. This method can not only solve the calculation problem result from the large DOFs of train but also make it convenient to modeling the long and heavy-haul train.

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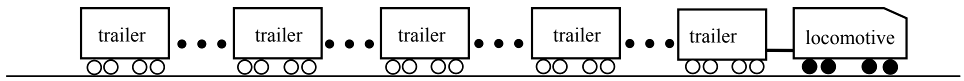

Figure 1: Diagram of train

Modular Modeling Method Based on Circular-Variable

For a passenger train, it normally includes decades of vehicles, while there are hundreds of vehicles and several locomotives distributing among the train of the freight train. With the running of heavy-haul train of 20000tons/train in our country, the length of one train will close to 300 vehicles and can reach kilometers. The diagram of train can be seen in Fig.1. If the train consists of n vehicles (locomotive and cars) and each vehicle owns m DOF, it means there are $m \times n$ DOF for the whole train system. The equations of motions of the train system are generally expressed as:

$$[M]\ddot{Y} + [C]\dot{Y} + [K]Y = \{P\} + \{F\} \tag{1}$$

Where, $[M]$, $[C]$, $[K]$, are mass matrix, damping matrix and stiffness matrix of the one vehicle with $m \times n$ orders, they can be described respectively:

$$[M] = \begin{bmatrix} m_1 & \dots & 0 & \dots & 0 \\ \dots & \dots & \dots & \dots & \dots \\ 0 & \dots & m_i & \dots & 0 \\ \dots & \dots & \dots & \dots & \dots \\ 0 & \dots & 0 & \dots & m_n \end{bmatrix}_{(m\times n)\times(m\times n)} \qquad [C] = \begin{bmatrix} c_1 & \dots & 0 & \dots & 0 \\ \dots & \dots & \dots & \dots & \dots \\ 0 & \dots & c_i & \dots & 0 \\ \dots & \dots & \dots & \dots & \dots \\ 0 & \dots & 0 & \dots & c_n \end{bmatrix}_{(m\times n)\times(m\times n)}$$

$$[K] = \begin{bmatrix} k_1 & \dots & 0 & \dots & 0 \\ \dots & \dots & \dots & \dots & \dots \\ 0 & \dots & k_i & \dots & 0 \\ \dots & \dots & \dots & \dots & \dots \\ 0 & \dots & 0 & \dots & k_n \end{bmatrix}_{(m\times n)\times(m\times n)}$$

The DOF variables, external forces and interaction forces between every vehicle can be described respectively:

$$Y = \begin{Bmatrix} y_1 \\ \dots \\ y_i \\ \dots \\ y_n \end{Bmatrix}_{(m\times n)\times 1} \qquad \{P\} = \begin{Bmatrix} p_1 \\ \dots \\ p_i \\ \dots \\ p_n \end{Bmatrix}_{(m\times n)\times 1} \qquad \{F\} = \begin{Bmatrix} f_{1\leftarrow 2} \\ \dots \\ f_{i-1\rightarrow i} + f_{i\leftarrow i+1} \\ \dots \\ f_{n-1\rightarrow n} \end{Bmatrix}_{(m\times n)\times 1}$$

It is difficulty for the actual computer to deal with a $(m \times n) \times (m \times n)$ matrix once a time. So the traditional modeling method of train is not suitable.

Now, we make some adaptation disposal and the motion equation (1) can be decomposed into n subequation:

$$[m_i]\{\ddot{y}_i\}+[c_i]\{\dot{y}_i\}+[k_i]\{y_i\}=\{p_i\}+\{f_i\}\quad (i=1\ldots n) \tag{2}$$

The interaction forces between every vehicle are:

$$\{f_i\}=\begin{cases}\{f_{1\leftarrow 2}\} & i=1\\ \{f_{i-1\rightarrow i}+f_{i\leftarrow i+1}\} & 1<i<n\\ \{f_{n-1\rightarrow n}\} & i=n\end{cases}$$

In the equation, $\{y_i\}$ is sets of DOF of the *i*th vehicle, $[m_i]$, $[c_i]$ and $[k_i]$ are mass matrix, damping matrix and stiffness matrix of the *i*th vehicle with *m* orders, $\{p_i\}$ is the external force acting on the *i*th vehicle, $\{f_{i-1\rightarrow i}\}$ and $\{f_{i\leftarrow i+1}\}$ are the interaction forces between adjacent vehicles of *i*th vehicle. (Of course for leading vehicle and trailing vehicle, there is only one interaction force between adjacent vehicles).

According to the equation (2), we can consider one car as a basic integral unit and separate the train system into n independent unit which can be calculated separately. Each vehicle's calculation will circularly use the same DOF variables (the number of DOF variables normally be decided by the vehicle having the most DOF. If one vehicle's DOF less than the number of DOF variables, the plus DOF variables will be set at zero). Once a vehicle's calculation is completed, the result will be saved as temporary variables (it will be transferred by the next step, the initial value of integral and the calculation of inter-vehicle suspension force both are transferred by the temporary variables), then the DOF variables will be released to the next calculation, it will not get into the next integral step until all the vehicles among the train have done the calculation. The next integral step will follow the same mode as the previous step until the whole integral calculation is accomplished. In the process of the entire integral calculation, the DOF variables being used will not increasing with the increase of train formation. Consequently, the calculation problems due to the "DOF blast" of long and heavy-haul train can be solved. We called the integral method as circular-variable method.

The most advantage of circular-variable method is good at solve of the modeling of long and big train. But for the mixed marshalling train with various vehicles, it is willing to help but the body is weak. The structure and parameters of each vehicle in one actual train will not be consistent with each other, epically for the freight train. Therefore, we built a model base of locomotives and rolling stocks (all the styles can be included). When we make a dynamic simulated calculation, what we require only is to set up order number of corresponding vehicle's style according to the train formation. It is not requires to build a new model and modify the program if there are some changes of train formation. The only thing we should do is to alter the definition of the formation. It is convenience for us to modeling the mixed marshalling train. This modeling method is called modular modeling.

Thus it can be seen that circular-variable method made the best of the modeling of long and big train, but it is not fit of the mixed marshalling train. However, the modular modeling method is just the opposite. There will be some limited if either of the method is used, but all the problems can be solved if both of the methods are adopted. We called the combination of the two methods as "Modular Modeling Method Based on Circular-Variable". The flow chart of program can be seen in Fig.2.

The advantage of the method is that it not only makes the numerical simulation of long and heavy-haul train dynamic behavior possible and fast, but also makes the train modeling more convenient.

The Advantages of Train Dynamics Model Coupled in Three Dimensional Spaces

The study on the train dynamics was arisen along with the development of heavy-haul transportation. In order to solve the safety problems in heavy-haul transportation, many countries have done a lot of research works on the train dynamics since the 70's of last century, such as American, Canada, Australia and Soviet Union. American have started its train dynamics plan in 1970 that is organized by the AAR, Association of American Railroads. The plan which lasted for ten year has set up some different models according to special aims. These models include longitudinal model (quasi-dynamic and dynamic), quasi-steady lateral stability model and vertical dynamics model. They considered the longitudinal, lateral and vertical dynamics as different parts. In fact, some vehicles maybe on the straight line or curve, and some others maybe stay on the ramp when a train running on the railway line, so the whole train will not be shown as straight line or plane. Accordingly, the dynamics behaves in longitudinal, lateral and vertical are so closed that has effect on each other. There will some localization if we don't consider dynamics reciprocity of the train in three directions.

We can modeling the long and heavy-haul train as simple as single vehicle recur to the "circular variables method" and "modular modeling method" adopted in this article. We can take various needed factors into consideration (such as straight line, curve, ramp and the space line which is made up of different lines; uniform speed, acceleration, deceleration and the multiple variable speed operation; wheel-rail contact relation, railway track irregularities, crosswind, characteristics of coupler, characteristics of haul, characteristics of brake, and so on), we could modeling the long and heavy-haul train system in which three dimensions are considered. Therefore, we can do an embedded study on the dynamics of long and heavy-haul

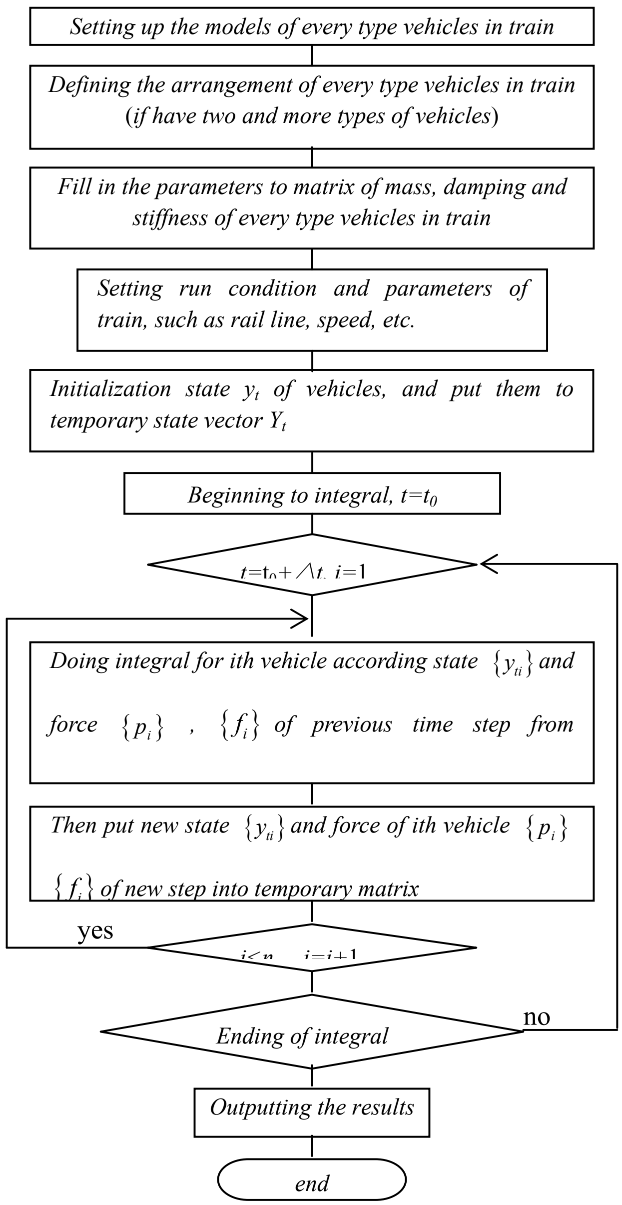

Figure 2: Flow chart of simulation

train:

- Take wheel-rail contact relation into consideration, we could do an analysis of wheel-rail dynamic interaction by creep theory and we can also considerate the effect of track irregularities. The comprehensive influences that result from the longitudinal, lateral and vertical dynamic interaction are fully considered.

- Do a complete study on the changing process of the safety index (such as wheel-rail lateral force, derailment coefficient and reduced rate of wheel load), when heavy-haul trains running on a line which is described as: "straight line-transition curve-circular curve-transition curve-straight line".
- Make a research on the change law of safety index when heavy-haul trains running in the straight line, curve, ramp and the space line made up of different lines with non-steady state, such as uniform speed, acceleration, or deceleration. Thus some advices for the optimization of train operation in different lines could be achieved.
- Make a research on the change law of safety index when heavy-haul trains running at various degrees of crosswind. Thus some advices for the speed limit could be achieved.
- Make a research on the change law of safety index when there are various heavy-haul trains formation.
- Make a research on the change law of safety index when train running at various statuses, including coupler clearance, characteristics of buffer, propagation characteristics of brake wave and relief wave in the brake system, traction characteristic curve, and so on. Therefore, we can put forward some reasonable suggestions for the optimum design of brake system, haul system and coupler and draft gear.

Dynamic Performances Analysis of Long and Heavy-Haul Train

Based on the theory analysis and simulation soft package of train dynamics, author have made a general dynamic simulation of long and heavy-haul train. During the simulation, the rail-wheel force, interaction forces between adjacent vehicles, motions of bodies such as car-body, bogie frame and wheelset can be output. The major dynamic performances of long and heavy-haul train are generalized as following (The detailed analysis will be expatiated in the full-article):

Ride Comfort

The ride comfort analysis of long and heavy-haul train is focused on the Sperling index and vibration acceleration.

(1) When a train running through a line with ramp, the ride comfort of vehicles in different location have remarkable differences.

(2) While a train running through a curve, the lateral acceleration and Sperling index are shown to be various and both of them are vibration with low frequency, especially when the train at the transition curves or circular curves. The vertical ride comfort often has a little change.

(3) The ride comfort is not the same while a train passed by the same position of line through different operation mode (such as uniform speed, acceleration, or deceleration). It's indicated that not only the lateral comfort but also the vertical comfort have a remarkable effect on the speed and haul or brake force. Train with coasting has a better performance than ones with hauling or braking.

(4) The style of mixed marshalling has some important effect on the ride comfort of train. The comfort of vehicle which is closed to the locomotive is worse than that far away the locomotive.

(5) The simulation result shown that the ride comfort of single vehicle is better than that of a train.

(6) Take the same light vehicles for object, the ride comfort of train is more or less the same, no matter where they are placed.

Dynamic Stability

(1) It is obvious that the result of train is different from single vehicle, especially when the train at traction or brake condition.

(2) It's indicated that the critical speed of light vehicle is less than that of heavy vehicle. It is mean that the hunting stability of light vehicle is worse than that of heavy vehicle.

(3) The mixed marshalling of light and heavy vehicles has effect on the stability of a train. It is pointed that the stability of light vehicles placed into the front and back of train is worse than that of light vehicles placed into the middle of train. So in order to increase the stability of mixed marshalling train, the light vehicles should be placed into the middle of train.

(4) Results shown that the safety indexes in dynamic curve negotiation are various while the train at the curve. Take one vehicle for study object, we can know that the safety indexes of the vehicle are changing with time. In other words, Vehicles at the straight line have a good safety indexes, others at the transition curve and circular curve have a worse safety indexes. Especially, the indexes are dynamic change when train at the transition curve while that are normally stable at the straight line and circular curve.

Analysis of Running Safety

(1) Ramp has an obvious effect on the running safety of train. The vehicles in straight line often have a better safety indexes than ones in the transition areas,

especially for the index like derailment coefficient, reduced rate of wheel load, wear index and coupler forces. This is because of the changing of railway profiles.

(2) The safety indexes are not the same while trains passed by the same position of line through different operation mode. Take straight line for example, train with coasting has a better safety performances than ones with hauling or braking, such as the lateral displacement of wheelset, wheel-rail lateral force, wheel-axle lateral force, derailment coefficient. However, the reduced rate of wheel load of acceleration is better than that of coasting and deceleration. The wear index of acceleration is worse than that of coasting and deceleration.

(3) Whether the longitudinal coupler force or the lateral coupler force, train with coasting is less than ones with acceleration and deceleration.

(4) Train formation has an effect which is can not be ignored on the running safety of train.

Other Conclusions

(1) The curve radius has some to do with the ride comfort. The bigger the curve radius is the better the ride comfort are.

(2) The length of transition curve has an important effect on the critical speed of the train. The speed will increase with the growth of length of transition curve.

(3) The relationship between safety indexes and curve radius has the same changing trend as the length of transition curve.