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고속전철용 집전시스템의 동적 해석

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Dynamic Analysis of Current Collection System in High Speed Train

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Summary

Dynamic characteristics of current collection system is one of the major factors which decide the performance of high speed train. To find good design parameters of the current collection system design guide is prepared through the engineering analysis in this study. The analysis starts from the statics of catenary system which results in the sinusoidal variation of stiffness, which is inherently nonlinear Mathieu equation. Simple physical models of rigid trolley wire and Mathieu equation are considered. To simulate the dynamic response of current collection system, numerical integration based on central difference method and modal analysis are presented. The calculated results of central difference method show superior to those of Euler based algorithm.

1. Introduction

Understandings on the dynamics of current collect system, i.e., the interaction between catenary system and pantograph is an essential part of high speed train technology, which decides the maximum speed of high speed train and causes a lot of failure or malfunction. Assurance of contact between pantograph and trolley wire, whatever speed or conditions, should be satisfied for reliable and fault free high speed train. But, the contact and separation between two parts and stiffness variation make this problem nonlinear. In mechanical system this nonlinearity is prevalent and makes it difficult to find the solutions.

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Study on the current collection system can not be attractive one as far as high speed train is a practical use at that country. Japan have developed a lot of pantographs and catenary systems. Also, the dynamic simulation method developed in Japan for current collection system is on the basis of Euler Algorithm. [1] The developed algorithm was focused on the calculation of separation and contact between pantograph and trolley wire as well as the displacements of trolley wire and pantograph. But, Euler algorithm can not help avoiding larger numerical error which depends on the choice of numerical time step. Choi [2] developed a similar numerical algorithm on the based of central difference method which can accomodate the nonlinearity. European technology relating to this dynamic analysis is known to use modal analysis.[3]

In this paper, Overall figure on the dynamics of current collect system is described and compared with the results of each analyzed methods. At first the stiffness variation as pantograph moves is calculated by finite element method. And, from simple modeling of current collection design guide was established. Numerical simulations on the basis of numerical integration and modal analysis also described for the comparison of each method.

2. Statics of catenary system

The catenary system for high speed train is composed of catenary wire, auxiliary wire and trolley wire, which are connected by hangers or droppers. Each wire deflects small due to its weight. Hanger or dropper makes this deflection flat, but the connection point can not avoid mass concentration, resulting in abrupt stiffness variation.

For the design of catenary system the deflection and the stiffness variation of each wire should be predicted.[4] A finite element program is developed to calculate the deflection and the stiffness of the catenary system at each contact point between pantograph and trolley wire. Catenary wire, auxiliary wire and trolley wire can be modeled as a string component, and hanger or dropper can be assumed rigid body or rod component which can resist axial force. Since all are assumed linear the calculation can be easily performed. Only the difference of the program compare to a general finite element method program is the inclusion of repetitive calculation as pantograph pass by.

Fig. 1 and 2 shows the calculated results of the deflection and the stiffness of the simple catenary system of TGV. It shows the largest deflection and the lowest stiffness occurs at the center of span. And small changes followed by the existence of hanger.

The variation of stiffness of catenary system is due to span length and the number of hangers including the design parameters of tension and wire density.

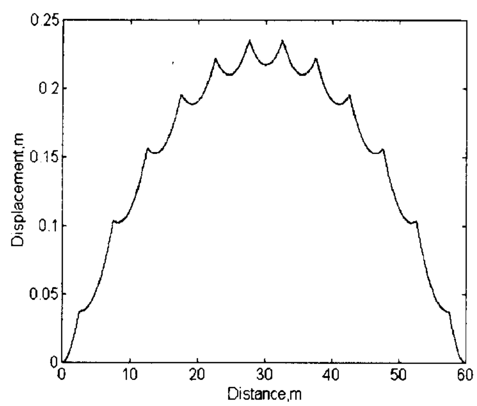

Fig.1 Displacement of trolley wire due to static uplift force in simple catenary
: l=63(m), T=1000(kg), ρ =0.988(kg/m), P_o=5.5(kg)

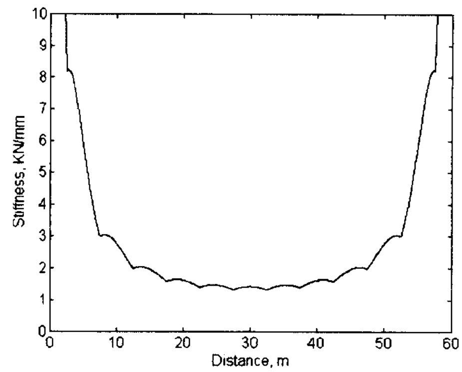

Fig.2 Stiffness variations in simple catenary : l=63(m), T=1000(kg), ρ =0.988(kg/m), P_o=5.5(kg)

3. Analytical dynamic models of current collection system

Simple dynamic models of current collection systems are considered in order to characterize the dynamic interaction of pantograph and catenary system.

3.1 Rigid trolley wire

Fig. 3 depicts a moving pantograph beneath a sinusoid rigid wall.

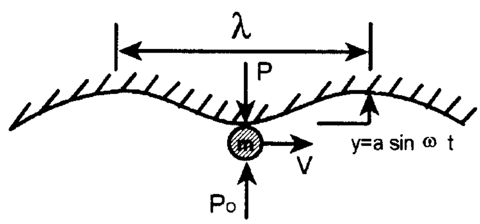

Fig.3 Moving mass on rigid sinusoidal wall

The sinusoid represents a periodic variation of trolley wire which can be represented as a function of x with the parameters of amplitude, a and period, λ .

$$y=a \sin \frac{2\pi x}{\lambda} \qquad (1)$$

If a pantograph moves with velocity V and lift force, P_o, the difference between the inertia force and the lift force will be contact force.

$$m\frac{d^2y}{dt^2} = P_0 - P \tag{2}$$

and $$\frac{dy}{dt} = \frac{dy}{dx}\frac{dx}{dt} = V\frac{dy}{dx}$$

then Eq. (2) can be as follows ,

$$mV^2\frac{d^2y}{dx^2} = P_o - P \tag{3}$$

The contact between pantograph and trolley wire means positive contact force, P physically. The condition of positive contact force, P should satisfy the following inequality equation.

$$\frac{P_0}{\left(\frac{2\pi}{\lambda}\right)^2 V^2 m} > a \tag{4}$$

Eq. (4) means that the assurance of contact requires the flatness of wire, larger lift force, small pantograph mass as speed increases. But, there is no rigid trolley wire with perfect flat. Therefore, it means that we have to use catenary system which has stiffness.

3.2 Time varying stiffness in current connection system

The result of finite element method for static analysis of catenary system shows that the stiffness varies as pantograph moves. Higher stiffness is at the end of span and lower one is at the mid span. This can be modeled as a harmonic variation of stiffness as shown in Fig. 4

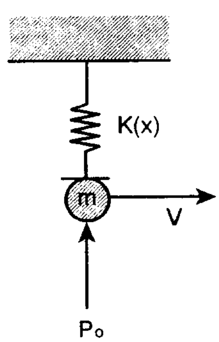

Fig.4 Moving mass beneath varying stiffness

Above can be modeled as a Mathieu equation

$$m\frac{d^2y}{dt^2} + K\left(1 + \varepsilon\cos\frac{2\pi V}{l}t\right)y = P_o \tag{5}$$

Assuming the solution of equation (5) as a sum of a constant term and a sinusoid term the displacement of contact point as follows

$$y(t) = \frac{P_o}{K}\left[1 + \frac{\varepsilon^2}{2}\,\frac{1}{1 - \frac{M}{K}\left(\frac{2\pi V}{l}\right)^2 - \frac{\varepsilon^2}{2}} - \frac{\varepsilon}{1 - \frac{M}{K}\left(\frac{2\pi V}{l}\right)^2 - \frac{\varepsilon^2}{2}}\cos\frac{2\pi V}{l}t\right]$$

(6)

In equation (6), the zero numerator means infinite displacement of the contact point, which means resonance. Therefore, the resonant speed will be as follows.

$$V_o = \frac{l}{2\pi}\sqrt{\frac{K}{M}}\sqrt{1 - \frac{\varepsilon^2}{2}} \tag{7}$$

To increase the resonant speed higher stiffness of trolley wire and light pantograph are required, also the variation of the stiffness should be minimized. The resonant speed does not mean the initial speed of separation between pantograph and trolley wire. If the inertia force of the pantograph, which can be calculated from the known displace ment of pantograph, is greater than the lift force, the separation between pantograph and trolley wire can start. From the above reasoning if the speed of train is greater than the following value, there is a possibility of separation

$$V_d = \frac{V_o}{\sqrt{1+\varepsilon}} \tag{8}$$

4. Numerical simulation of current collect system

A real mechanical system constitutes a governing equation of motion as a partial differential equation. But the partial differential equation can hardly be solved especially for the case of dimensional variation or complex boundary conditions. Consequently general vibration analysis is achieved by the discretization of continuous system as multiple degrees of freedom. As the method of finding the dynamic response of the system numerical integration method or modal analysis are needed. Modal analysis can easily characterize the dynamics of the system. Therefore, modal analysis is generally used for the system design. But modal analysis can not say anything about nonlinear system. Numerical integration method can be applied to nonlinear system. But cares for the adoption of algorithm and time step should be kept.

Catenary/pantograph system has a complex equation of motion since it is a combination of string and rod. Also multiple static boundary conditions and moving boundary condition. Also, the contact force between pantograph and trolley wire is a implicit equation of the displacement of pantograph and trolley wire. This requires special numerical technique for finding the dynamic characteristics of the current collection system.

Japanese researches on this theme uses Euler algorithm. But European researches including France and Germany are known to use modal analysis. Euler algorithm is simple but can bring numerical error. Here central difference algorithm is suggested and modal analysis are also applied to analyze the current collect system.

4.1 Numerical integration by central difference method

Under the assumption of followings catenary system can be modeled as a multiple degree of freedom system as like Fig. 5.

- Catenary wire is a string which can not sustain compression or moment.
- Catenary moves only up and down.
- Catenary system is composed of finite member of lumped mass.
- Hanger is a massless rigid body.
- The stiffness can be calculated from the displacement of the only neighboring load mass.
- Damping is a viscous type.

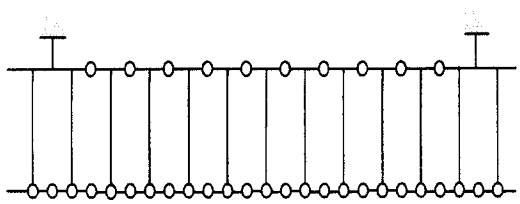

Fig. 5 Discretized model for simple catenary

system

In a mass point the equation of motion is as follows

$$m_i \ddot{x}_i(t) = F_{s,i} + F_{d,i} + F_{p,i}$$

$$F_{s,i} = -\sum_i \frac{T_j}{d}\{2x_i(t) - x_{i+1}(t) - x_{i-1}(t)\} \qquad (12)$$

$$F_{d,i} = -\sum_i C_j\{2\dot{x}_i(t) - \dot{x}_{i+1(t)} - \dot{x}_{i-1}(t)\}$$

where, $F_{s,i}$ is spring force, $F_{d,i}$ is damping force, and $F_{p,i}$ is the contact force at i th mass. The contact force can be calculated by using linear interpolation technique.

$$F_{p,i} = aP_m(x)$$

And for the pantograph the equation of motion as follows from the model as shown in Fig. 6

$$M_p \ddot{Y}(t) = P_o - P_m(t) \qquad (13)$$

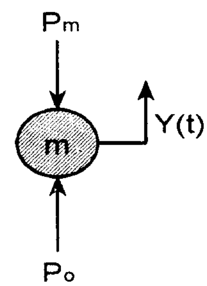

Fig.6 Single degree of freedom pantograph

Above two equation for catenary and pantograph should be solved simultaneously for every point masses of catenary system. Considering the effect of contact and separation, central difference method is adopted to solve the dynamic response of current collection system. Applying central difference algorithm to equation (12) results,

$$x_i(t+\Delta t) = 2x_i(t) - x_i(t-\Delta t) + \frac{\Delta t^2}{m}\{F_{s,i} + F_{d,i} + F_{p,i}\} \qquad (14)$$

Equation of motion for pantograph also can be solved using central difference method.

$$Y(t+\Delta t) = 2Y(t) - Y(t-\Delta t) + \frac{\Delta t^2}{M_p}\{P_o - P_m(t)\} \qquad (15)$$

The displacement of pantograph can be calculated under the assumption of rigid connection between two neighboring mass points. During the calculation if contact force is negative, and it means separation in physical sense. A ratio between the duration of separation and the pantograph running time is the separation ratio. Fig. 7-a and 7-b shows the calculated results of central difference method for displacement of trolley wire and contact force variation as pantograph passing.

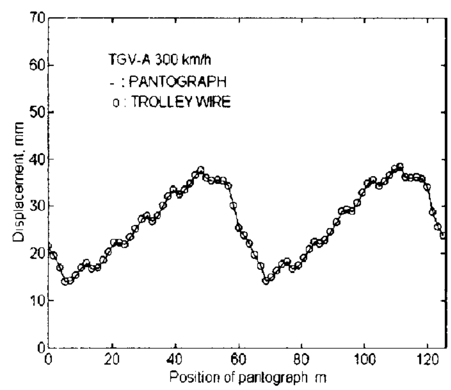

Fig.7-a Displacement of trolley wire and pantograph for simple catenary.
: L=63(m), T=1000(kg), ρ =0.988(kg/m), P_o=5.5 (kg)

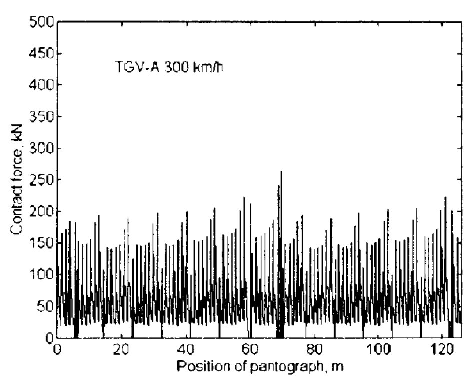

Fig.7-b Variation of contact force in simple catenary : L=63(m), T=1000(kg), ρ =0.988(kg/m), P_o=5.5(kg)

The figure shows two components of sinusoid, one is due to span, the other is due to hanger length. And the figure also shows that there is a lot of chance of separation near span end and hanger point. Fig. 8 depicts the comparison of the results of Euler algorithm and those of central difference method. The results of central difference method shows some periodicity compared to those of Euler algorithm. Through the results for the 7th pantograph passing as in Sinkansen. This explains that error in accumulates in Euler algorithm as time goes by. But central difference method does not.

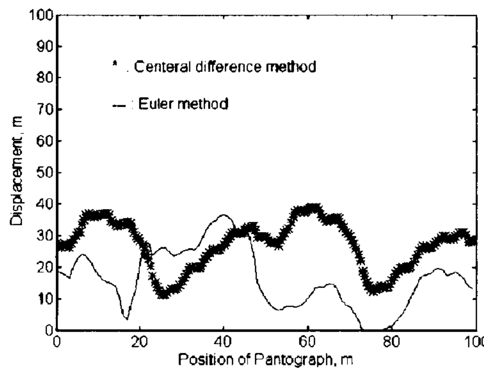

Fig.8 Displacement of trolley wire at the position of 7th pantograph passing : L=50(m), T=1000(kg) , ρ =0.988(kg/m), P_o=5.5(kg)

4.2 Modal analysis

Dynamic characteristics of current collection system can be investigated by using modal analysis. Modal analysis gives the natural frequencies and the mode shapes which can easily generate the forced response of the system. Also the result can be easily compared and modified through experiment. Modal analysis can decide the design parameters of catenary system and pantograph

But the separation of pantograph from trolley wire can not be figured out since this is a nonlinear phenomenon. Here, an application of modal analysis to current collection system is tried. At first, from the finite element model the stiffness of the system can be calculated. Consistent mass matrix of the system can also be calculated from the finite element model.

Mass matrix and stiffness matrix can give the natural frequencies and the mode shapes by solving eigenvalue problem.

Fig. 9 shows the displacement of trolley wire calculated by numerical integration method and the forced response by modal analysis.

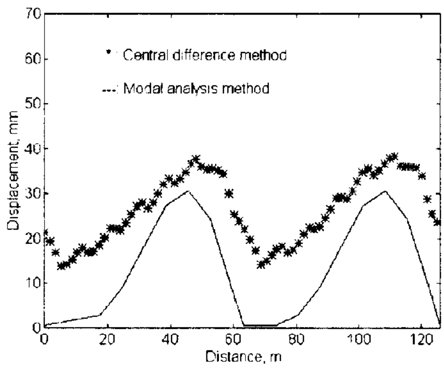

Fig.9 Displacement of trolley wire by numerical intergration and by modal analysis

5. Conclusion

The dynamics of current collection system is a major factor to decide the performance of high speed train. Assurance of contact and tracking of pantograph to catenary system should be guaranteed. It is difficult to using an active control system, i.e., feed back control system because of high speed. On the contrary a passive control, i.e., a proper of design parameters should be selected.

Especially the dynamics of current collection is inherently nonlinear which makes dynamics analysis difficult. The time variation of stiffness of catenary system should be adjusted by considerate choice of design parameters of a catenary system, i.e., tension, wire density, span and hanger length.

As an analysis tool, central difference method are proposed to validate the superiority compared to Euler algorithm or modal analysis. Developed algorithm shows the minimum accumulation of errors, also can easily calculate the separation ratio which is one of the important parameters characterizing the performance of current collect system.

But numerically calculated results should be confirmed to experimental results. Also a mechanical problem involving nonlinearity should be analyzed based on the experiment or experience. More detailed analysis of pantograph including the nonlinear effect of joint, clearance, and coupling should be necessary. In catenary system the effect of presag or overlap should also be considered.

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