Robust Control of the Contact Force of an Active Pantograph for High Speed Trains

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Acknowledgments

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Myat Thiri Ko

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Abbreviations

HILS	Hardware in the loop simulation
VSS	Variable structure system
SRL	Symmetric root locus
AC	Alternative current
DC	Direct current
LQR	Linear quadratic regulator

Chapter 1

Introduction

1.1 Introduction

High speed trains are a fast transport system in many countries and is getting popular all over the world. With the development of railway technology, electric field trains have proven to have many advantages over other forms of transport systems, i.e. high energy efficiency, high specific installed power, low maintenance cost, more responsive control, no emissions in urban areas, and energy-saving by regeneration brake systems. However, it also has some drawbacks: high capital cost of providing the energy distribution, complex to operate in regions with different electrical supply standards and poor current collecting quality when running above the originally intended operational speed. Today, electrically powered trains are widely used on the main railway lines in many countries. [1,2,3]

Fig 1.1 High Speed Train in Japan

Figure 1.1 shows a high-speed train with the pantograph and catenary system. The functions of pantograph is to collect the electric energy from the catenary and transfer it to the locomotives motors, so that they have enough energy to operate. The pantograph-catenary system is an elaborately-designed system which can keep a good quality of electricity transmission at relatively high speeds. The pantograph can automatically be raised from the folded position and work at a certain range of the height while sustaining a constant uplift force. The catenary is a well-suspended structure kept in a desired geometry.

For high-speed trains, active control of the pantograph is crucial technology to collect electrical current from the overhead contact wire supported by vertical droppers, hangers and cantilevers. When the pantograph runs along the catenary, it is fluctuated due to aerodynamic force, propagation and reflection of the wave on the catenaries, changes in the dynamics characteristics of the catenary system depending on the position, etc. An excessively large contact force can damage both in the pantograph and the catenary or may cause a severe accident like contact wire breaking in the worst case. On the other hand, if the contact force is too small, the pantograph and catenary easily lose their contact state. The state the pantograph and catenary are in the non-contact state is called contact loss.

If the dynamic interaction between pantograph and catenary is not constrained within an acceptable range, in some extreme cases, not only a high maintenance cost can be expected but also serious structural damage can appear. With the development of the railway technology in recent years, the operational speeds for most railway line have significantly been increased world-widely, so the pantograph-catenary becomes one of the key factors which decide the cost of infrastructure and maintenance, and limit the operational speed. Therefore, it is quite important for both engineers and researchers to investigate the dynamic behavior of the pantograph-catenary system to keep the contact tight and stable. The increase of the static contact force, which might be considered as a possible solution for this problem, is not an efficient way, because it increases mechanical abrasive wear and produces an excessive uplift of the contact wire.

Therefore, maintaining the contact force in an admissible region is crucial for high speed trains and thus modeling and control of active pantograph-catenary systems have been taken much attention from many researchers. So far, some models and controllers for the systems have been proposed. For example, Arnold and Simeon developed a rather rigorous model with PDEs and DAEs and then proposed a numerical solution method [4], Makino et al. developed a wing-shaped low-noise collector and proposed an H_∞ controller with a disturbance observer [5], Yamashita et al. developed a low-noise active pantograph, and then applied a PID controller or an impedance control method [6], Chartter et al. proposed a controller based on the back-stepping method together with a high-gain observer [7], Allota, Pisano, et al. proposed higher order sliding mode controllers [8]-[10], Sanchez-Rebollo et al. proposed a hardware-in-the-loop strategy with a PID controller [11].

In order to regulate the contact force, the authors and the Railway Technical Research Institute have developed an active pantograph using a pneumatic actuator, and presented modelling and a robust regulator with a rigid frame model. In this thesis, three different types of control strategies are introduced. The design and performance of an active pantograph which collects current for high-speed train are considered. A dynamic model of the pantograph/catenary system is described and control objectives are established.

1.2 Objectives

As mentioned above, the modelling and the study of the pantograph-catenary system enables the saving of time and cost. By modelling these elements, engineers can make modifications and test new implementation to improve the quality of real pantographs, making them more perfect. The main objectives of this project can be summarized as presented below:

- Modelling the active pantograph with flexibility: to maintain the contact force in an admissible region
- Analyzing the pantograph-catenary system
- Applying different kinds of control theory to the controller design to regulate the more robust contact force
- Developing the best control configuration and control strategy

1.3 Contributions

This thesis investigates a dynamic behavior of the contact force variations of pantograph-catenary system based on numerical studies. There are three different types of controller together with an observer, which are introduced. They are

(1) Linear state feedback controller with sliding mode observer,

(2) Sliding mode servo controller with sliding mode observer and

(3) Optimal servo system based on sliding mode control with sliding mode observer. Although the first two control methods of the active pantograph systems in this thesis only regulate the contact force under model uncertainty or disturbance, but the last controller, optimal servo system, can realize to track the reference signal optimally by making efficient use of the active force.

The model of the pantograph was recovered from the work developed by the master student *Shun Nagayoshi*. Once the model has been obtained, the next stage is to investigate the dynamic properties both analytically from a systems-theory point of view and numerically. The system is studied with the computational tool *Matlab / Simulink* that enables knowing the response of the pantograph to the catenary's action.

1.4 Thesis Organization

This thesis is organized into five chapters:

Chapter 1 describes an introduction to all worked about the high speed train.

In Chapter 2, a basic structure of the pantograph head and the contact wire (catenary system) is described. The mathematical model of the pantograph head and the catenary system are constructed. Furthermore, a mathematical model of the pantograph and catenary has integrated to get the contact state because the train is considered as moving state. The stiffness of the overhead contact wire in catenary system is a main source of the variation of the pantograph-catenary system. Hence, it is emphasized that the fluctuation of the equivalent stiffness between the pantograph head and the overhead contact wire, makes it difficult to control the contact state of the system.

Chapter 3 proposes the linear state feedback controller together with the sliding mode observer, taking account of the flexibility of the articulated frame in our pantograph. It is emphasized that one of the key points is to regulate the contact force in the nominal model without perturbation. A physical interpretation of the pole-zero cancellation in the transfer function is also given.

Chapter 4 is composed of two different sections. In the first section, we propose a sliding mode controller together with the sliding mode observer, taking account of the flexibility of the articulated frame in the actual pantograph. An introduction to the variable structure system (VSS) is described. The condition to ensure the switching surface, so-called reachability condition, is also described. The reduced order sliding dynamics is formulated. The proposed controller achieves the robust output (contact force) by pole-zero cancellation during sliding mode. Secondly, we analyze the robust stability of the active pantograph system using Lyapunov method.

Chapter 5 describes an optimal servo system based sliding mode controller together with a sliding mode observer. It is pointed out through our analysis of the plant and the closed-loop system using SRL (symmetric root locus) technique that pole-zero cancellations play an important role to control the contact force.

Chapter 6 summarizes the contribution of the thesis and points out some key ideas proposed in this thesis.

Chapter 2

Mathematical Model of the Pantograph and Problem Formulation

2.1 Pantograph Catenary interaction

Figure 2.1 shows a high-speed train with the overview of the pantograph and catenary system. The stationary system that consists of poles and the wires with the electric power supply is called catenary. The train is connected to the catenary system via pantograph which is mounted on the roof of the train. The catenary has two wires, the contact wire which is connected to the pantograph and the messenger wire above the contact wire is linked together over the droppers. The pantograph catenary is designated to transfer electric current to the train. As a contact pair is always moving, it is important to keep the contact between pantograph and catenary tight and stable.

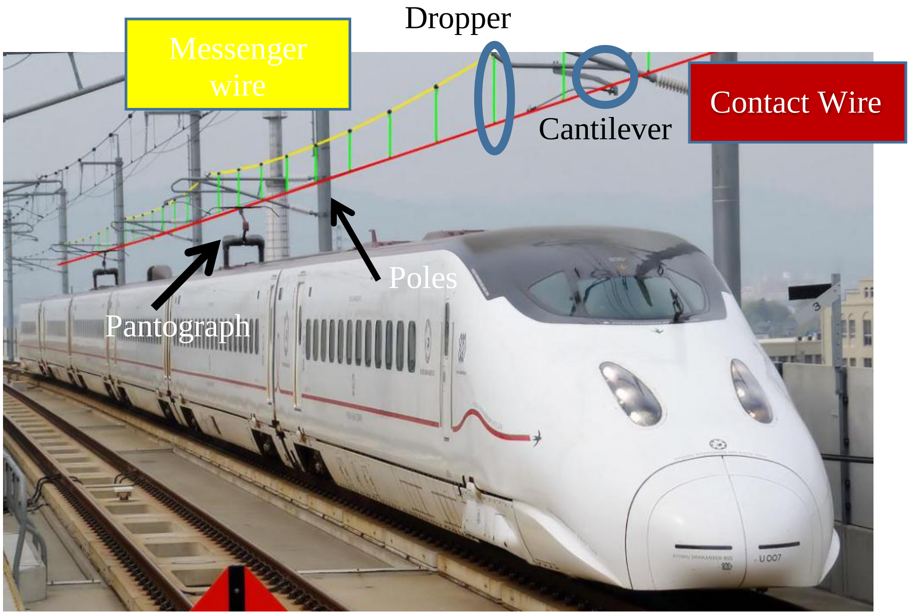

Fig 2.1 The train with pantograph and catenary system

2.1.1 Pantograph

The aim of pantograph system is to collect electrical current from the catenary cable system. In order to collect the current and not to interfere with the passing non-electric train under the overhead lines, the main frame is fold-able and can vertically raise the pantograph head a significant distance. To achieve good current collection, the pantograph head is sprung and is pushed against the overhead line. The drive, usually operated by compressed air from the brake system, is used to power the system to raise or fall, and provides sufficient uplift force to keep the contact between overhead line and pantograph head. Nowadays, there are several types of pantographs existing, but the principles are nearly the same. [2]

The pantograph consists of a part of body that come in contact with the overhead catenary and a frame that supports it. The frame is divided into upper frame and lower frame. The main spring acts to lift the entire pantograph upwards. For a passive pantograph, the only way to avoid the loss of contact at higher speed is to reduce both the mass of the pantograph head and the frame, but this is limited by the required current-carrying capacity of the pantograph.

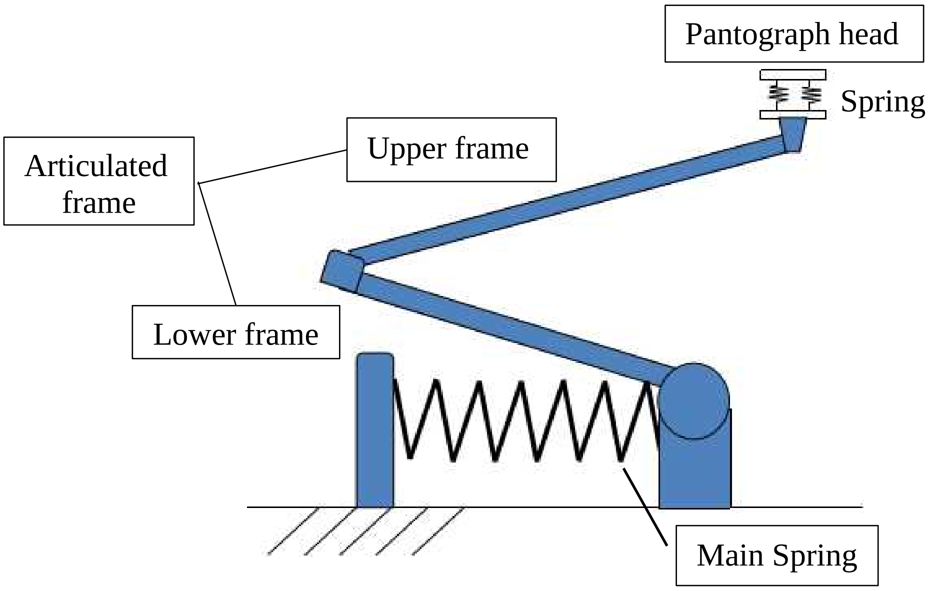

Fig 2.2 Pantograph

2.1.1.1 Force exerted on the pantograph

The pantograph suffers different types of forces which have different natures. They can be classified as static loads [12], dynamic loads and aerodynamic loads. The application point of these forces is established in the contact point with the catenary wire. A summarized explanation of these forces is presented below:

1. Static contact forces: These loads are exerted on the pantograph when it raised still. This force is applied on the point where the overhead's strips contact with the catenary wire. A perfect pantograph should keep a constant static contact force across its route.
2. Dynamic contact forces: This component of the force depends on the nature of the contact and on the speed of the train.
3. Aerodynamic contact forces: This force must be differentiated from the aerodynamic force that opposes to the train's course. This aerodynamic force is a vertical force and it opposite to the vertical movement of the pantograph as consequence of the aerodynamic effects. These aerodynamic effects increase with the train speed, therefore a proper design both of the train and the pantograph needs to take account to them.

2.1.2 Active Pantograph

As mentioned above, the pantograph doesn't control the variations of the contact force by itself. In order to control the contact force between the pantograph and the catenary, the active pantograph with the pneumatic actuator have been developed. It was found through some experiments that the frame had flexibility which could not be ignored to control the contact force.

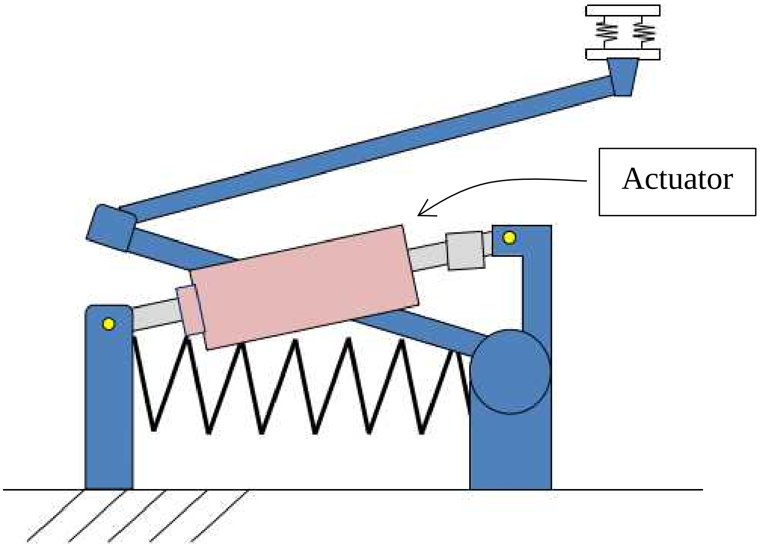

Fig 2.3 Active pantograph

2.1.3 Catenary

The catenary mainly consists of the contact wire, a continuous conduction which transfers electric current to the moving train through the pantograph, and some other supporters to support the weight of the contact line and to keep the contact wire in a certain shape at certain positions. [3] The structure of the catenary shown in fig 2.4. In general, a catenary is composed of one or two wires that ensure the power transmission to the pantograph, and it also counts with one or two complementary wires that are charged of maintaining the horizontality of the contact wire, as observed in fig 2.4.

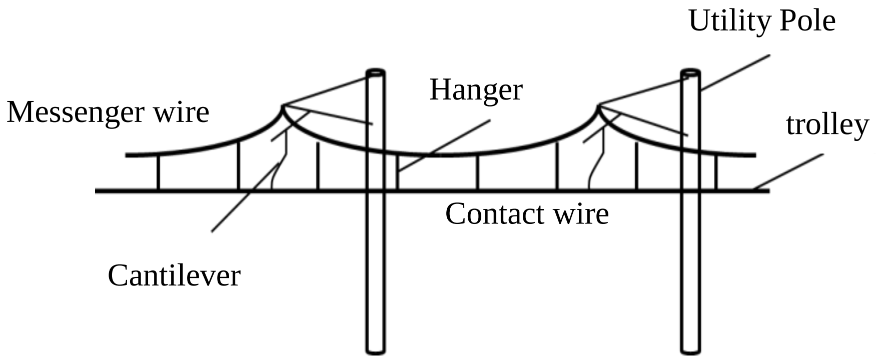

Fig 2.4 Catenary system

The upper wire is the messenger wire and the lower wire is the contact wire where the contact with the pantograph take places. The catenary is widely used in railways permitting operation at voltages above AC 1000V and DC 1500V, by which trains get sufficient power to run at a high speed. To achieve good current collection, it is necessary to keep the contact wire geometry within the definite limits. This is usually achieved by supporting the contact wire from above by a second wire known as catenary wire (or messenger wire).

2.1.3.1 Types of catenaries

1 (Tramway) Catenary

It is the simplest catenary, it consist on a wire tended between two supports. It is used in low speed tracks. It greatest advantage is the presence of stiff points at the supports, what leads to the interruption of the contact between the pantograph and the catenary.

2 AC Catenary

When running at high speeds becomes, the use of tramway catenaries is no longer an option. This is due to the fact that catenaries start oscillating when the train starts to run at high speeds. This can be solved by using an additional wire which positioned over the contact wire with the mission of holding the latter. Two kinds of catenary can be used, AC (Alternative current) or DC (Direct current) catenaries. It is easier to boost the AC voltage than the DC voltage, so it is send more power with AC lines. As AC is easier to transmit over long distances, it is an ideal medium for electric railway’s supply. This catenary is the most used in long lines requiring from trains running at high speeds.

3 DC Catenary

DC catenary, is preferred in shorter lines, urban systems and tramways. As shorter line trains required less power, DC catenaries supply the enough power to the railway’s traction. It must be mentioned that corrosion is an important factor to be considered in DC systems.

2.2 Mathematical Model of the System

2.2.1 Mathematical model of the catenary system`

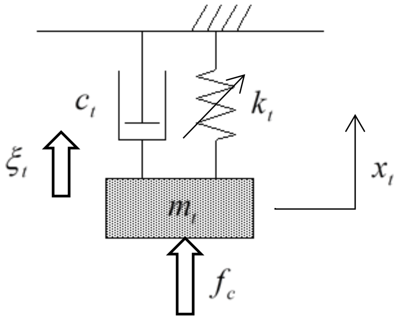

Fig 2.5 Catenary model

A catenary is a complex periodic structure. The catenary model described here is use a simplified spring, mass and damper model as shown in fig 2.5. The catenary mass and the damper are time-invariant elements and the spring is as the time-varying element k_t. The equation of motion can be written as

$$m_t\ddot{x}_t = -c_t\dot{x}_t - k_t x_t + f_c + \xi_t \tag{2.1}$$

where $\xi_t = \Delta k_t x_t$ defines as the uncertainty/ disturbance due to the change of the equivalent stiffness k_t of the catenary system. The state equation can be expressed as

$$\begin{bmatrix}\dot{x}_t\\ \ddot{x}_t\end{bmatrix} = \begin{bmatrix}0 & 1\\ -\dfrac{k_t}{m_t} & -\dfrac{c_t}{m_t}\end{bmatrix}\begin{bmatrix}x_t\\ \dot{x}_t\end{bmatrix} + \begin{bmatrix}0\\ \dfrac{1}{m_t}\end{bmatrix} f_c + \begin{bmatrix}0\\ \dfrac{1}{m_t}\end{bmatrix}\xi_t \tag{2.2}$$

$$= \mathbf{Ax}_t + \mathbf{h}_t f_c + \mathbf{d}_t \xi_t$$

where t is taken as the short form of the trolley (Catenary).

2.2.2 Mathematical model of pantograph system

Taking account of the flexibility in the frame, a three degree of freedom model is developed as shown in fig 2.6, where m_s, m_{f1} and m_{f2} are masses of the pantograph head, the upper frame and lower frame, respectively, f_a is static uplift force generated by the main spring which is denoted as the actuator force (the other variables are defined as shown below in table 2.1). In this research, the disturbance such as aerodynamic fore, static loads, etc… which are neglected.

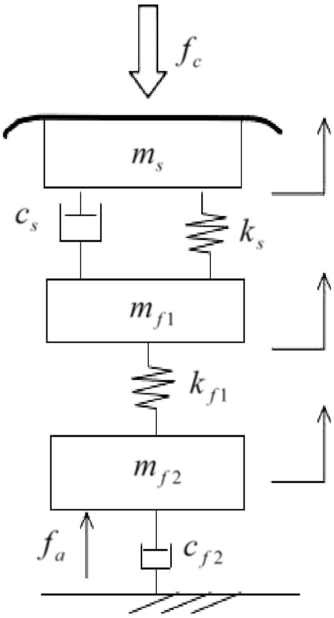

Fig 2.6 Pantograph model

The equation of motion of the system can be written as

$$\begin{aligned} m_s\ddot{x}_s &= -c_s(\dot{x}_s - \dot{x}_{f1}) - k_s(x_s - x_{f1}) - f_c \\ m_{f1}\ddot{x}_{f1} &= -c_s(\dot{x}_{f1} - \dot{x}_s) - k_s(x_{f1} - x_s) - c_{f1}(\dot{x}_{f1} - \dot{x}_{f2}) - k_{f1}(x_{f1} - x_s) \\ m_{f2}\ddot{x}_{f2} &= -c_{f1}(\dot{x}_{f2} - \dot{x}_{f1}) - k_{f1}(x_{f2} - x_{f1}) - c_{f2}\dot{x}_{f2} + f_a \end{aligned} \tag{2.3}$$

Hence the following linear and time-invariant of the state space representation was derived to

$$\begin{bmatrix} \dot{x}_s \\ \ddot{x}_s \\ \dot{x}_{f1} \\ \ddot{x}_{f1} \\ \dot{x}_{f2} \\ \ddot{x}_{f2} \end{bmatrix} = \begin{bmatrix} 0 & 1 & 0 & 0 & 0 & 0 \\ -\frac{k_s}{m_s} & -\frac{c_s}{m_s} & \frac{k_{f1}}{m_s} & \frac{c_{f1}}{ms} & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ \frac{k_s}{m_{f1}} & \frac{c_s}{m_{f1}} & -\frac{(k_s+k_{f1})}{m_{f1}} & -\frac{(c_s+c_{f1})}{m_{f1}} & \frac{k_{f1}}{m_{f1}} & \frac{c_{f1}}{m_{f1}} \\ 0 & 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & \frac{k_{f1}}{m_{f2}} & \frac{c_{f1}}{m_{f2}} & -\frac{k_{f2}}{m_{f2}} & -\frac{(c_{f1}+c_{f2})}{m_{f2}} \end{bmatrix} \begin{bmatrix} x_s \\ \dot{x}_s \\ x_{f1} \\ \dot{x}_{f1} \\ x_{f2} \\ \dot{x}_{f2} \end{bmatrix} + \begin{bmatrix} 0 \\ -\frac{1}{m_s} \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix} f_c + \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ \frac{1}{m_{f2}} \end{bmatrix} f_a \tag{2.4}$$

$$= \mathbf{A}_p \mathbf{x}_p + \mathbf{h}_p \mathbf{f}_c + \mathbf{b}_p \mathbf{f}_a$$

where p is used as the short form of the pantograph model. The physical parameters used here are shown in Table 2.1.

Table 2.1 Physical parameters

Catenary stiffness	k_t	[N/m]	Catenary damping	c_t	[Ns/m]
Mass of catenary	m_t	[kg]			
Shoe-upper frame stiffness	k_s	[N/m]	Shoe-upper frame damping	c_s	[Ns/m]
Mass of shoe	m_s	[kg]	Mass of upper frame	m_{f1}	[kg]
Upper frame-lower frame stiffness	k_{f1}	[N/m]	Upper frame-lower frame damping	c_{f1}	[Ns/m]
Mass of lower frame	m_{f2}	[kg]	Lower frame damping	c_{f2}	[Ns/m]
Contact force	f_c	[N]	Axis force	f_a	[N]
Displacement of contact wire/shoe	x_{ts}	[m]	Displacement of upper frame	x_{f1}	[m]
Displacement of lower frame	x_{f2}	[m]	Uncertainty/disturbance due to catenary’s stiffness variation	ξ_t	[N]

2.2.3 Composite model of pantograph and catenary

Consider the train situation is always moving, it is desired to control the contact force variations and not to get the contact losses between the pantograph and catenary system, the overhead contact wire and pantograph have to keep in contact with each other. Therefore, it is determined to combine the catenary model which described in fig 2.5 and pantograph model which described in fig 2.6. Figure 2.7 shows the combine model when the contact wire and the pantograph are in contact state. Assuming that the overhead contact wire and the shoe on the pantograph head are connected all the time, the state vectors can be redefined as

$$x_t = x_s = x_{ts} \tag{2.5}$$

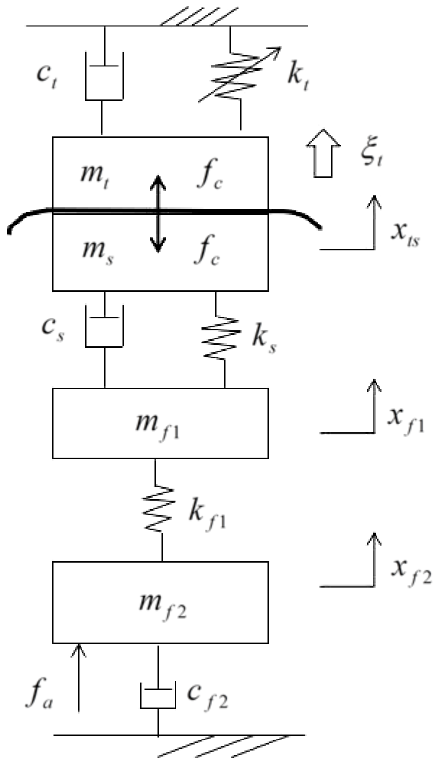

Fig 2.7 pantograph-catenary model

The origin in the coordinates is the equilibrium point, the equations of motion of the masses are given by

$$(m_t + m_s)\ddot{x}_{ts} = -(-c_t + c_s)\dot{x}_{ts} - (k_t + k_s)x_{ts} + c_s\dot{x}_{f1} + k_s x_{f1} + \xi_t \tag{2.6}$$

$$m_{f1}\ddot{x}_{f1} = c_s\dot{x}_{ts} + k_s x_{ts} - (c_s + c_{f1})\dot{x}_{f1} - (k_s + k_{f1})x_{f1} + c_{f1}\dot{x}_{f2} + k_{f1}x_{f2} \tag{2.7}$$

$$m_{f2}\ddot{x}_{f2} = c_{f1}\dot{x}_{f1} + k_{f1}x_{f1} - (c_{f1} + c_{f2})\dot{x}_{f2} - k_{f1}x_{f2} + f_a \tag{2.8}$$

Taking the state vector as,

$$\mathbf{x} = \begin{bmatrix} x_{ts} & \dot{x}_{ts} & x_{f1} & \dot{x}_{f1} & x_{f2} & \dot{x}_{f2} \end{bmatrix}^T \tag{2.9}$$

The state equation is

$$\begin{aligned}\dot{\mathbf{x}} &= \begin{bmatrix} 0 & 1 & 0 & 0 & 0 & 0 \\ -\dfrac{k_t+k_s}{m_t+m_s} & -\dfrac{c_t+c_s}{m_t+m_s} & \dfrac{k_s}{m_t+m_s} & \dfrac{c_s}{m_t+m_s} & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ \dfrac{k_s}{m_{f1}} & \dfrac{c_s}{m_{f1}} & -\dfrac{k_s+k_{f1}}{m_{f1}} & -\dfrac{c_s+c_{f1}}{m_{f1}} & \dfrac{k_{f1}}{m_{f1}} & \dfrac{c_{f1}}{m_{f1}} \\ 0 & 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & \dfrac{k_{f1}}{m_{f2}} & \dfrac{c_{f1}}{m_{f2}} & -\dfrac{k_{f1}}{m_{f2}} & -\dfrac{c_{f1}+c_{f2}}{m_{f2}} \end{bmatrix}\mathbf{x} \\ &\quad + \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ \dfrac{1}{m_{f2}} \end{bmatrix} f_a + \begin{bmatrix} 0 \\ \dfrac{1}{m_t+m_s} \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix} \xi_t \\ &= \mathbf{A}\mathbf{x} + \mathbf{b}u + \mathbf{d}_t \xi_{\mathrm{t}} \end{aligned} \tag{2.10}$$

Since the contact force includes inertial force of the overhead contact wire and pantograph head, in order to obtain an expression of the contact force, we need the following equations of motion with respect to each mass independently.

$$m_t \ddot{x}_t = -c_t \dot{x}_t - k_t x_t + f_c - \Delta k_t x_t \tag{2.11}$$

$$m_s \ddot{x}_s = -c_s(\dot{x}_s - \dot{x}_{f1}) - k_s(x_s - x_{f1}) - f_c \tag{2.12}$$

From these equations, it follows the contact force equation can be represented by

$$\begin{aligned} f_c = \frac{1}{m_t+m_s}&\left\{(c_t m_s - m_t c_s)\dot{x}_{ts} + (k_t m_s - m_t k_s)x_{ts} + m_t c_s \dot{x}_{f1} + m_t k_s x_{f1}\right\} \\ &- \frac{m_s}{m_t+m_s}\xi_t \end{aligned} \tag{2.13}$$

The contact force state equation can be given by

$$\begin{aligned} f_c &= \frac{1}{m_t + m_s}\begin{bmatrix} k_t m_s - m_t k_s & c_t m_s - m_t c_s & m_t k_s & m_t c_s & 0 & 0 \end{bmatrix}\mathbf{x} - \frac{m_s}{m_t + m_s}\xi_t \\ &= \mathbf{cx} + d\xi_t \end{aligned} \tag{2.14}$$

2.2.4 Stiffness variations of the catenary

Figure 2.8 shows the diagram of the catenary stiffness, when the train speed is 360km/h. The distance between two poles is set to 50meters. The wire length is usually from 1 km to 1.5 km, depending on the temperature ranges. When the pantograph moves along the overhead wire, its stiffness variation produces a periodic excitation which leads to the vibration of the pantograph and the fluctuation of the contact force. A main source of vibration is the stiffness variation of the contact wire along the span. The stiffness of the overhead wire is the minimum at the middle of the span and it is the maximum at the around the support tower, which means that the catenary stiffness k_t is always change with the time. In this thesis, the variations of the catenary stiffness is treated as the disturbance. And then consider the fluctuation range of the contact force due to the changes of the stiffness variations. The catenary stiffness k_t varies between

$$200 \le k_t \le 2000 \tag{2.15}$$

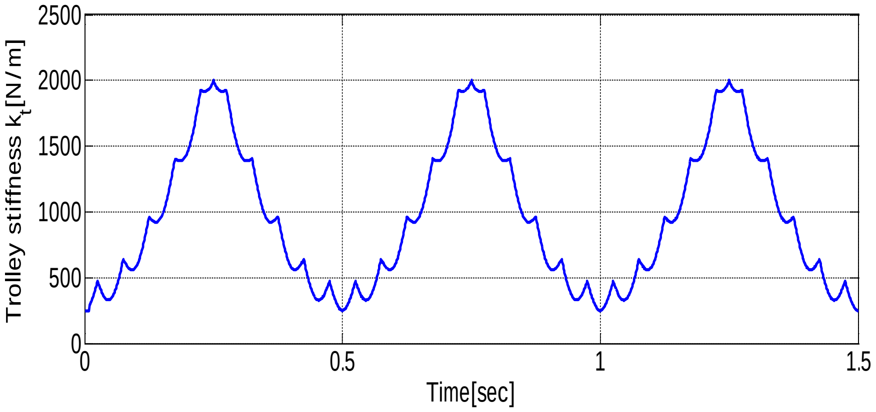

Fig 2.8 Catenary Stiffness

2.3 System analysis of the open loop control system

In this section, we do analyze the state equation of the pantograph catenary system (eq 2.10) and the output equation (eq 2.13). The parameters are set according to the values from Table (2.2) and d stands for the disturbance input to the pantograph-catenary model. From the identification experiments of these parameters, the equivalent stiffness coefficient of the catenary, k_t is defined as a time varying parameters. But in this thesis, we take $k_t = 1100 N/m$ as for the nominal case.

Table (2.2) Designated parameter values

m_t	$100kg$	m_s	$2.13kg$	m_{f1}	$6kg$	m_{f2}	$10kg$
k_t	$200N/m$	k_s	$3800N/m$	k_{f1}	$19218N/m$		
c_t	$100Ns/m$	c_s	$60Ns/m$	c_{f1}	0	c_{f2}	$80Ns/m$

Design on the open loop control system of the pantograph-catenary system, we can consider the control system in two different ways as follow;

(1) Control analysis from disturbance input d to the output y and

(2) Control analysis from control input u to the output y.

2.3.1 From Disturbance input to Output

The equation of the open loop gain from the disturbance input to contact force (output of the system) can be written as

$$G(s) = \mathbf{c}(s\mathbf{I} - \mathbf{A})^{-1}(-\mathbf{D}) + (-d) \tag{2.16}$$

From (eq 2.16), the poles and zeros of the transfer function from the disturbance input to the contact force are obtained as follows

$$p_{dy} = [-5.17 \pm 102.27i \quad -3.85 \pm 36.39i \quad -0.76 \pm 1.05i]$$
$$z_{dy} = [-18.94 \pm 157.53i \quad -1.93 \pm 64.0i \quad -4.43 \quad 0]$$

Figure 2.9 shows the bode diagram of the transfer function from the disturbance input to the contact force.

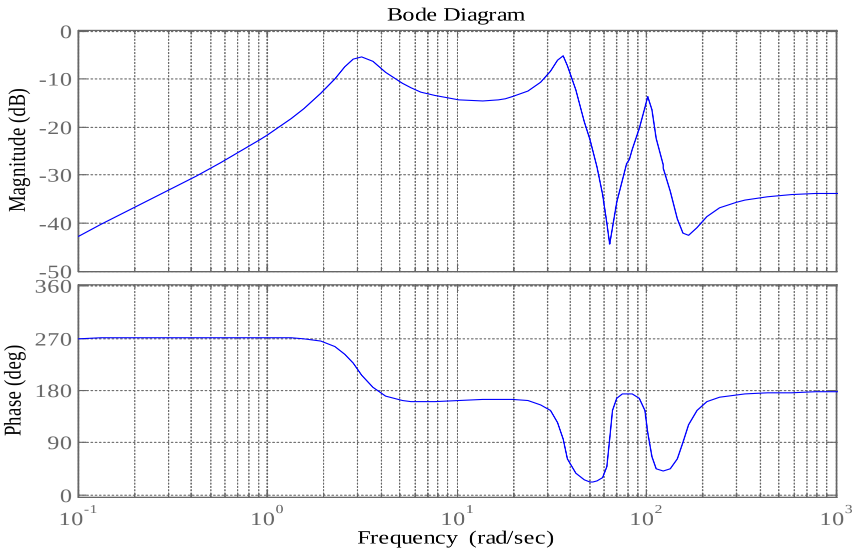

Fig 2.9 Bode plot for the open loop transfer function from the disturbance input to the contact force output

According to this diagram, it can be seem that the gain continues to decrease in the low frequency until it reaches to the zero point of the origin because of the direct term which we mentioned in (eq 2.14). It also should be noted that the relative degree between the uncertainty/ disturbance ξ_t and the contact force f_c is zero because the uncertainty ξ_t appears in the output equation (eq 2.14).

2.3.2 From Control input to Contact force

The equation of the open loop gain from the control input to contact force (output of the system) can be written as

$$G(s) = \mathbf{c}(\mathbf{s}I - \mathbf{A})^{-1}\mathbf{b} \tag{2.17}$$

From (eq 2.17), the poles and zeros of the transfer function from the control input to the contact force are obtained as follows

$$p_{uy} = \left[-5.17 \pm 102.27i \quad -3.85 \pm 36.39i \quad -0.76 \pm 1.05i\right]$$

$$z_{uy} = \left[-633.33 \quad -0.50 \pm 1.32i\right]$$

Figure 2.10 shows the bode diagram of the transfer function from the disturbance input to the contact force.

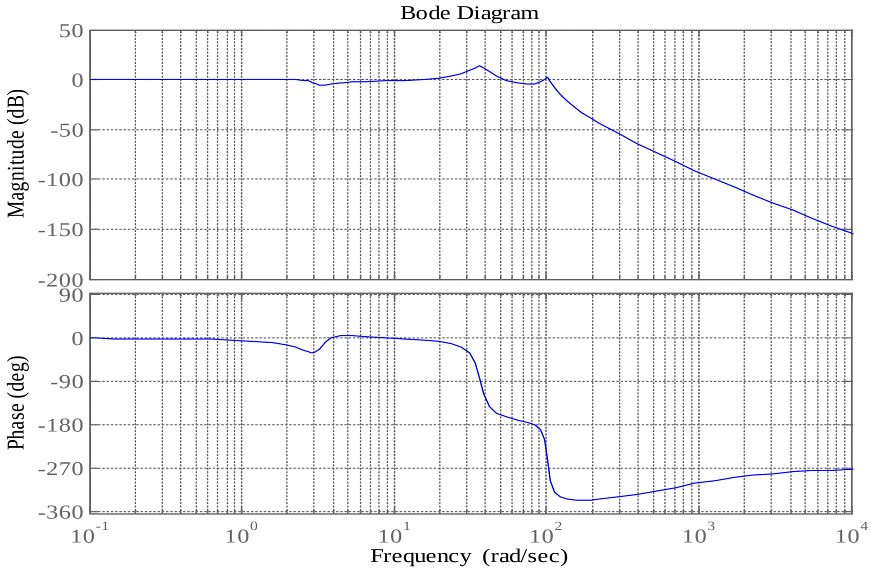

Fig 2.10 Bode plot for the open loop transfer function from the control input to the contact force output

With the state equation (eq 2.10) and the output equation (eq 2.14), the numerator polynomial of the transfer function from the control input to the contact force is given by

$$\begin{vmatrix} \mathbf{A} - s\mathbf{I} & -\mathbf{b} \\ \mathbf{c} & 0 \end{vmatrix} = (m_t s^2 + c_t s + k_t)(c_s s + k_s)(c_{f1} s + k_{f1}) \tag{2.18}$$

where $c_{f1} = 0$ from our identification experiments, and thus the zeros of the transfer function are obtained as follows

$$s = -\frac{k_s}{c_s}, \frac{-c_t \pm \sqrt{c_t^2 - 4m_t k_t}}{2m_t} \tag{2.19}$$

It should be noted that two complex zeros of the transfer function are the same as the poles of the nominal catenary subsystem given by (eq 2.11), and that the relative degree is three. If $c_{f1} \neq 0$, the relative degree would be four. On the other hand, the relative degree of the transfer function from the disturbance ξ_t to the contact force is zero as mentioned above. In general output regulation or disturbance rejection problems, the relative degree and pole-zero cancellation play an important role in controller design. That is, from the above observations, we can see that it is impossible to reject the disturbance completely in our system, because the relative degree of the transfer function from the control input to the contact force is less than that of the transfer function of the disturbance. Furthermore, in order to reduce the effect of the disturbance on the contact force, some of the closed-loop poles should be assigned in exactly the same location as the catenary poles, yielding pole-zero cancellation.

2.4 Problem formulation

The main reason of the implementation of an active control system is the reduction of the standard deviation of the contact force between the pantograph and catenary, hence reducing the contact variation and holding the contact force as constant as possible. The disturbances are mainly caused by the droppers and poles.

In control theory, the disturbance is normally considered in the way as shown in fig 2.11. As the exact input of the disturbance into the pantograph-catenary model is known from section (2.2.3).

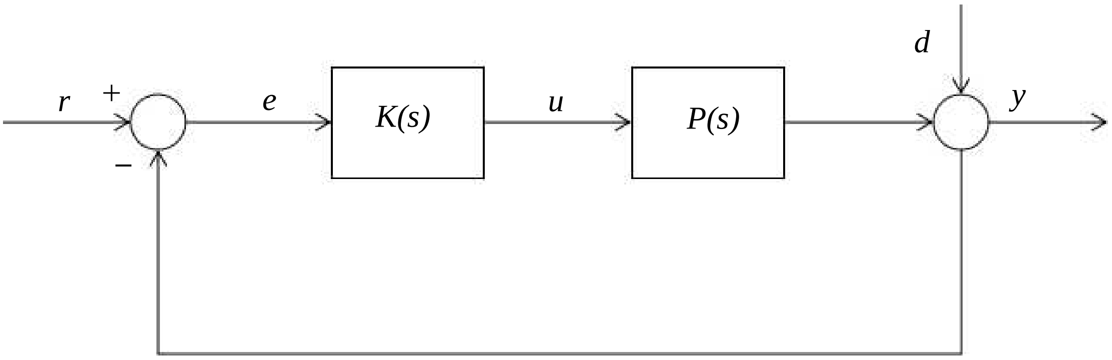

Fig 2.11 Closed loop control system with the disturbance added to the output signal

The active pantograph control system is mainly used closed-loop feedback control, in which it is difficult to keep the contact force constant. Because of the comprise between the stability and the performance of a feedback control system. For an active pantograph, different control strategies will lead to different results. Here in this thesis, we introduce three different types of control strategies. They are

(1) Linear state feedback controller with sliding mode observer,

(2) Sliding mode servo controller with sliding mode observer and

(3) Optimal servo system based on sliding mode control with sliding mode observer.

Each of them above gives a good performance of the pantograph catenary interaction which will be discussed in chapter 3, 4 and 5.

2.5 Summary

In this chapter, a basic structure of the pantograph head and the contact wire (catenary system) is described. The mathematical model of the pantograph head and the catenary system are constructed. Furthermore, a mathematical model of the pantograph and catenary has integrated to get the contact state because the train is considered as moving state. The stiffness of the overhead contact wire in catenary system is a main source of the variation of the pantograph. Hence, the fluctuation of the equivalent stiffness between the pantograph head and the overhead contact wire, make it happen a problem to control the contact state of the system. In section 2.3, a problem formulation of the pantograph-catenary system proposed and then a numerical analysis of the open-loop pantograph-catenary system has described. Moreover, the relative degree of the transfer function and the pole-zero cancellation plays as an important role from the viewpoint of output system are also discussed.

Chapter 6

Conclusion

6.1 Summary of Study

The main objective of this thesis is to investigate the robust contact force of an active pantograph for high speed trains. The work includes the studies on the structures and the dynamics behavior of the active pantograph-catenary system. Three different control strategies have proposed, taking account of the flexibility of the articulated frame in the actual pantograph. Firstly, the development of the contact force control of an active pantograph using a linear state feedback controller together with the sliding mode observer has been considered and secondly, the development of an active pantograph using sliding mode controller together with the sliding mode observer has been improved where the disturbances and uncertainties were neglected. Finally, the development of a robust contact force control of an active pantograph using optimal servo system based sliding mode controller together with the sliding mode observer has been developed. It has been pointed out through our analysis that the pole-zero cancellations play an important role to control the contact force.

In chapter 2, the construction of mathematical model of the pantograph head and the catenary system is described. An active pantograph using pneumatic actuator is developed in this chapter, which is considered for the entire thesis. It is very important to control the contact force between the pantograph head and the overhead contact wire because the active pantograph system for the high speed train in this research is considered as moving state. After that, however, it was found through some experiments that the frame had flexibility which could not be ignored to control the contact force. The stiffness of the overhead contact wire in catenary system is a main source of the variation of the pantograph. Hence, the fluctuation of the equivalent stiffness between the pantograph head and the overhead contact wire, make it happen a problem to control the contact state of the system. The important measurements which are used in this thesis is also described. The problem formulation of the pantograph-catenary system is proposed.

Chapter 3 has mainly discussed the design of a linear state feedback controller together with the sliding mode observer. The main objective of this controller design is that the active pantograph can resist the disturbances/ uncertainties using optimal force, which is derived from the feedback state and can achieved the best theoretical performance. The theoretical background for both controller and observer are discussed with the figures. LQR (linear quadratic regulator) technique has been successively applied to the linear servo system. The problem of designing the sliding mode observer using VSS (variable structure control system) is considered. It has been emphasized that one of the key points to regulate the contact force is pole-zero cancellation in the nominal model without perturbation. Finally, the simulation results of the controller and observer, which is described with good performance results.

Chapter 4 has discussed two different sections: the sliding mode controller design and the stability of the system. Firstly, a sliding mode controller together with the sliding mode observer is proposed, taking account of the flexibility of the articulated frame in the actual pantograph. An introduction to the variable structure control system with sliding mode control is described. The reduce order sliding dynamics is formulated. It is also discussed the use of boundary layer design to avoid the chattering effects. The proposed controller achieves the robust output (contact force) by pole-zero cancellation during sliding mode. A physical interpretation of this pole-zero cancellation is also given, that is, the pantograph head follow the catenary mode without preventing its free motion. Then, the robust stability approach for the active pantographs system is analyzed. Lyapunov theory for stability analysis is used. One sufficient condition for asymptotic stability has been derived but still need other methods to prove more practical stability.

Chapter 5 has proposed a sliding mode controller using optimal servo control theory and sliding mode observer. The design of the controller in which switching function is mainly discussed, optimal linear gain and virtual plant system are included. LQR (linear quadratic regulator) technique has been successively applied to not only linear servo systems but also sliding mode control systems. The main advantages of this optimal sliding mode servo control is that they can provide a more robust optimal control to the system. The function of an optimal sliding mode control system is as follows: if the control system is dominated in the region of nominal part, the system behavior is mainly governed by optimal control. If the control system is dominated in the region of perturbations, sliding mode control will take over the main control task. A physical interpretation of this pole-zero cancellation is also given, that is, the pantograph head can follow the catenary motion not to prevent its free motion by assigning some of the closed loop poles on the catenary mode. The simulation results has confined the good performance and robustness of the proposed control system in the presence of variation of the catenary stiffness.

6.2 Future Work

There are some subjects to investigate in the future as follows:

1. To make sure of the effectiveness of the proposed controllers with some experimental setup such as HILS.
2. To choose more appropriate measurements (output variables) for the observer taking practical situations such as noise level into account.
3. To analyze the closed-loop stability much more rigorously dealing the plant as a time-varying system.

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