Numerical study on multi-pantograph railway operation at high speed

Zhendong Liu

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Preface

The work presented in this thesis was carried out between September 2013 and August 2015 at the Department of Aeronautical and Vehicle Engineering at KTH Royal Institute of Technology in Stockholm, Sweden.

It was supported by Royal Institute of Technology (KTH), Swedish Transport Administration (Trafikverket), Bombardier Transportation, Schunk group and mainly funded by China Scholarship Council (CSC). I would like to thank my main supervisor Prof. Sebastian Stichel in particular for giving me the opportunity to work as a PhD student and guiding me exploring the unknown world. I would like to give special thanks to my co-supervisors, Per-Anders Jönsson and Anders Rønnquist, for sharing their knowledge with me and helping me solve every problem I met during my work.

I am grateful for the support from all my colleges in our unit: Mats, Carlos, Evert, Roger, Matin, Alireza, Saeed, Tomas as well as all the former colleges in KTH Rail Vehicle unit. In addition, I would like to thank my friends: Petter Nåvik, Xinmin, Yuyi, Zhan, Wei, Zibo and Huina.

In the end, I want to show my most heartfelt gratitude to my parents and my wife, for their encouragements and supports in the past two years.

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Zhendong LIU
Abstract

Multi-pantograph operation allows several short electric multiple unit (EMU) trainsets to be coupled or decoupled to adapt to daily or seasonal passenger-flow variation. Although this is a convenient and efficient way to operate rolling stock and use railway infrastructure, pantographs significantly influence each other and even significantly change the dynamic behaviour of the system compared to single-pantograph operation in the same condition. The multi-pantograph system is more sensitive and vulnerable than the single-pantograph system, especially at high operational speeds or with pantographs spaced at short distances. Heavy oscillation in the system can result in low quality of current collection, electromagnetic interference, severe wear on the contact surfaces or even structural damage. The mechanical interaction between the pantograph and the catenary is one of the key issues which limits the maximum operational speed and decides the maintenance cost.

Many researchers have paid a lot of attention to the single-pantograph operation and have made great progress on system modelling, optimizing, parameter studies and active control. However, how the pantographs in a train configuration affect each other in multi-pantograph operation and which factors limit the number of pantographs is not fully investigated. Nowadays, to avoid risking operational safety, there are strict regulations to limit the maximum operational speed, the maximum number of pantographs in use, and the minimum spacing distance between pantographs. With the trend of high-speed railways, there are huge demands on increasing operational speed and shortening spacing distance between pantographs. Furthermore, it is desirable to explore more practical and budget-saving methods to achieve higher speed on existing lines without significant technical modification.

In addition to a literature survey of the dynamics of pantograph-catenary systems, this thesis carries out a numerical study on multi-pantograph operation based on a three-dimensional pantograph-catenary finite element (FE) model. In this study, the relationship between dynamic performance and other parameters, i.e. the number of pantographs in use, running speed and the position of the pantographs, are investigated. The results show that the spacing distance between pantographs is the most critical factor and the trailing pantograph does not always suffer from deterioration of the dynamic performance. By discussing the two-pantograph operation at short spacing distances, it is found that a properly excited catenary caused by the leading pantograph and the wave interference between pantographs can contribute to an improvement on the trailing pantograph performance. To avoid the additional wear caused by poor dynamic performance on the leading pantograph and achieve further improvement at high speeds, it is suggested to use the leading pantograph as an auxiliary pantograph, which does not conduct any electric current and optimize the uplift force on the leading pantograph. After a brief discussion on some system parameter deviations, it is shown that a 30% of speed increase should be possible to achieve while still sustaining a good dynamic performance without large modifications on the existing catenary system.
Keywords: numerical study, pantograph-catenary system, multi-pantograph operation, dynamic behaviour, high-speed operation.
Sammanfattning


Många forskare har forskat kring system med en strömavtagare i drift och har gjort stora framsteg när det gäller systemmodellering, optimering, parameterstudier och aktiv kontroll. Men det finns få studier som undersöker hur flera strömavtagare i drift påverkar varandra och vilka faktorer som begränsar antalet strömavtagare. För att undvika att riskera driftsäkerheten, finns det numera strikta regler för att begränsa största tillåtna hastighet, det maximala antalet strömavtagare i bruk, och det minsta avståndet avståndet mellan strömavtagare. Med utvecklingen av höghastighetståg, finns det stora krav på ökad hastighet och på att förkorta avståndet avståndet mellan strömavtagare. Dessutom är det önskvärt att undersöka mer praktiska och billigare metoder för att uppnå högre hastighet på befintliga linjer utan betydande tekniska ändringar.

Förutom en litteraturstudie kring dynamiken i strömavtagare-kontaktledningssystem, innehåller denna avhandling en numerisk studie av flera strömavtagare i drift baserad på en tredimensionell strömavtagare-kontaktledning finit element (FE) modell. I studien, undersöks förhållandet mellan dynamisk prestanda och några systemparametrar, dvs antal strömavtagare i bruk, hastighet och placering av strömavtagarna. Resultaten visar att avståndet mellan strömavtagarna är den mest kritiska faktorn, och den bakre strömavtagaren lider inte alltid av försämrad dynamisk prestanda. Genom att diskutera drift med två strömavtagare med kort avstånd, visas att en väl avvägd excitering av kontaktledningen via den ledande strömavtagaren och våginterferensen mellan strömavtagare kan bidra till en förbättring av prestandan på den bakre strömavtagaren. För att undvika ytterligare slitage orsakat av dålig dynamisk prestanda för den ledande strömavtagaren och för att uppnå ytterligare förbättring vid höga hastigheter, rekommenderas det att använda den ledande strömavtagaren som en extra strömavtagare, som inte leder någon elektrisk ström och optimera upplyftskraften för den ledande strömavtagaren. Efter en kort diskussion om vissa systemparametrars variation, visas att 30% hastighetsökning
bör kunna uppnås utan försämring av den dynamiska prestandan och utan stora förändringar på befintliga kontaktledningssystem.

**Nyckelord:** numerisk studie, strömavtagare-kontaktledningssystem, multi-strömavtagardrift, dynamiska beteenden, höghastighetsdrift.
Dissertation

This thesis consists of an introduction to the area of research, a summary of the present work and the following appended papers:

**Paper A**


All simulations were carried out by Jönsson, Liu and Nilsson. The paper was written by Liu under the supervision of Stichel, Jönsson and Rønnquist.

**Paper B**

Zhendong Liu, Per-Anders Jönsson, Sebastian Stichel and Anders Rønnquist, ‘Possible speed increase on soft catenary system with help of auxiliary pantograph’, *Proceedings of the 24th International Symposium on Dynamics of Vehicles on Roads and Tracks, IAVSD 2015, Austria*.

All simulations were performed by Liu. The paper was written by Liu under the supervision of Stichel, Jönsson and Rønnquist.

**Paper C**

Zhendong Liu, Per-Anders Jönsson, Sebastian Stichel and Anders Rønnquist, ‘On the implementation of an auxiliary pantograph for speed increase on existing lines’, *submitted for journal publication*.

All simulations were carried out by Liu. The paper was written by Liu under the supervision of Stichel, Jönsson and Rønnquist.
**Thesis contribution**

This thesis investigates the dynamic behaviour of railway pantograph-catenary system under multi-pantograph operation based on numerical studies. It contributes to the present research field as follows:

- A literature survey of multi-pantograph operation has been carried out. The relationship between dynamic performance and other parameters, i.e. the number of pantographs in use, running speed and the position of the pantographs, is studied.
- Through parametric studies on multi-pantograph operation, key factors which determine the dynamic performance of the entire system like, spacing distance between pantographs, the position of the pantographs and the operational speed, are found.
- By studying the two-pantograph system at short spacing distance between pantographs, the positive effects, i.e. proper excitation of the catenary and wave interference between pantographs, which can lead to the improvement of the dynamic performance are found.
- To allow the existing system to be qualified for a higher operational speed, two practical solutions, taking the leading pantograph as auxiliary pantograph and a small uplift force reduction applied to the leading pantograph, are proposed which promise a significant improvement of the system performance without much modification on the existing system.
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1 Introduction

Railway transport is a major mean of passenger and freight transport in many countries and is getting more and more popular all over the world due to its safety, efficiency and large capacity. With the development of railway technology, electrified trains have proven to have many advantages over other forms of traction 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 regenerative brake systems. However, it also has some drawbacks: high capital cost of providing the energy distribution system, lack of flexibility in the event of route disruption, 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, especially after introduction of electric multiple units (EMU) and the development of high-speed railways. [1-3]

On electrified railway lines, the electrical energy is transferred to the train from a continuous or nearly continuous conductor above or aside the track through a collector mounted on the train. Although there are many applications which have been used in railway systems, i.e. third conductor rail/contact shoe, trolley pole collector/overhead line and bow collector/overhead line, as shown in Figure 1.1, they have some mechanical and safety limitations, which severely restricts the operational speeds and risks people and animals in the neighborhood. Therefore, they are only used in low-speed local transport, such as metro and tram. Nowadays, the pantograph-catenary system, as shown in Figure 1.2, has become the only application in railway transport systems world-widely.

![Figure 1.1: Applications use for electric current collecting: (a) third conduct rail/contact shoe [4]; (b) overhead line/trolley pole collector [5]; (c) overhead line/bow collector [6].](image)

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 height while sustaining a constant uplift force. The catenary is a well-suspended structure kept in a desired geometry. As the pantograph is pressing against and running along the
catenary rather than fixed to it, the quality of energy transmission is directly determined by the contact performance between the two conductors. At high speeds, the dynamic interaction between pantograph and catenary becomes very pronounced and leads to not only poor power transition quality but also excessive wear on the contacting surfaces. The contact force is usually regarded as the best indicator of the contact performance. It is subjected to a large number of parameters, especially when the train runs at high speeds where the interaction between the two conductors is extremely aggravated. However, the contact force must not be too high, because high contact force leads to excessive mechanical wear which shortens the service life of the system. On the other hand, too low contact force can not only cause low quality of current collection but also electrical discharge which results in electrical erosion and serious electromagnetic interferences [1]. 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 [7]. With the development of the railway technology in recent years, the operational speeds for most railway lines have significantly been increased world-wide, so the pantograph-catenary system 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 behaviour of the pantograph-catenary system to keep the contact tight and stable.

![Image](a) Pantograph on X 2000 train [8]; (b) catenary in a railway station [9].

As the dynamic interaction between the pantograph and catenary is a very important issue for both system design and infrastructure operation, there are many numerical studies carried out for high operational speed, low maintenance costs, high reliability and flexible operation. Arnold and Simeon developed a method to present the dynamics based on coupled systems of partial and algebraic differential equations [10]. Collina and Bruni used penalty techniques and modal analysis in the numerical study [11]. Wu and Collina studied the application of actively controlled pantograph for high-speed operation [12-14]. Harrel and Drugge investigated the dynamic behavior of the pantograph-catenary system within a normal section and on section overlaps with a 2D model [15]. Pombo looked at the contact behavior at different positions and took environmental and track
perturbations into consideration [16]. Jönsson introduced a 3D finite element (FE) model to calculate the dynamic interaction between pantograph and catenary [17]. Cho investigated the influence of contact wire pre-sag on the dynamics [18]. Zhai discussed the influence of vibration from car body on the system [19]. Ding and Zhang showed the friction and wear behaviour between pantograph and catenary [20]. These studies involve in structure design, system optimization, system modeling, and control theory. Researchers have made great progress on the relevant issues. For instance, high speed catenary systems today allow trains to run at 350 km/h on some newly-built commercial lines or even 574 km/h during trials, active pantographs enable trains to run at a higher speeds without much modification on old systems, newly-designed pantographs can significantly reduce wear to extend the service life of the entire system, and multiple pantograph operation is widely adopted in some low-populated countries [21-24].

Multi-pantograph operation, which is widely used in many European countries, is one of the emerging topics which researchers focus on today. It allows several short electric multiple unit (EMU) trainsets to be coupled or decoupled to adapt to daily or seasonal passenger-flow variation. Although this is a convenient and efficient way to operate railway rolling stock and to use railway infrastructure, the pantographs significantly influence each other and even change the dynamic behaviour of the system compared to single-pantograph operation under the same conditions. For example, Manabe pointed out that resonances might occur in some speed ranges after on-track measurement with multiple pantographs [25, 26] and many tests and studies have shown that multi-pantograph operation does not have good contact performance between pantograph and catenary [27, 28]. Therefore, multi-pantograph operation is more sensitive and complex than the single-pantograph operation, especially at high operational speeds or with pantographs spaced at short distances. To avoid risking operational safety and provide more flexibility to rolling stock operation, a systematic investigation on multi-pantograph operation is desired.

In this thesis, a computational analysis of the dynamic interactions between pantograph and catenary under multi-pantograph operation is performed and parametric studies are carried out to address the influence of the parameters. Some positive effects, which can improve the dynamic performance to some extent, are found and addressed. In order to meet the need of speed increase on existing lines, a practical method, i.e. an auxiliary pantograph, is proposed and discussed. In Chapter 2, some fundamental knowledge and previous research regarding the dynamic interaction of the pantograph-catenary system is shortly summarized. In Chapter 3, a brief overview on modeling of the pantograph-catenary system is given and the fully three dimensional finite element (FE) model used in this thesis is described. In Chapter 4, an overview of multi-pantograph operation is given and the relationship between parameters, i.e. spacing distance between pantograph, running speed, the number of pantographs in use and the position of the pantographs during operation, is discussed. In Chapter 5, a proposal for speed increase is given by
taking advantage of some positive effects in multi-pantograph operation. In Chapter 6, a summary of the appended papers is given. Finally, in Chapter 7, some conclusions from the work are drawn and future work is proposed.
2 Interaction between pantograph and catenary

The pantograph-catenary system is designated to transfer electric current to the running train. As the contact pair is always moving, it is important to keep the contact between pantograph and catenary tight and stable enough to transmit electric power. The quality of the energy transmission and the yearly maintenance cost are directly determined by the performance of the interaction between the pantograph and the catenary. As the dynamic behaviour is determined by the designs of the structures of the system, the following sections describe some typical designs, basic vibrating theory as well as some methods to test and evaluate the dynamic interaction.

2.1 Introduction

The pantograph is an innovation of the trolley pole and the bow collector to keep electricity collecting safe and reliable at relatively high speeds. It is mounted on the roof of a locomotive or a car body and can be raised and lowered automatically. In order to collect the current and not to interfere with the passing non-electric trains under the overhead lines, the main frame is foldable and can vertically raise the pantograph head a significant distance. The structure of a pantograph is as shown in Figure 2.1. 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 vehicle's brake system, is used to power the system to raise or to 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. The conductor mounted on the pan-head pressing against the contact wire is called collector strip, which is usually made of graphite, to minimize the wear between pantograph and catenary under the electric load.

![Figure 2.1: Schunk WBL88 pantograph [15].](image-url)
The catenary mainly consists of the contact wire, a continuous conductor, which transfers electric current to the moving train through the pantograph or the like, 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. The structure of the catenary is as shown in Figure 2.2. 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 defined limits. This is usually achieved by supporting the contact wire from above by a second wire known as catenary wire (or messenger wire). Compared with the applications in trams and trolley pole buses for low speed traffic, the railway catenary has a relatively complex structure, such as special suspension and tensioning devices, as shown in Figure 2.3. There are several types of catenary systems existing in Sweden. The main types are SYT 7.0/9.8, SYT 15/15, ST 9.8/9.8 and ST 15/15, where SYT stands for a catenary with stitch wire, ST without stitch wire, as detailed in Table 2.1.

Figure 2.2: Basic components of the catenary in a span.

Figure 2.3: Tensioning device (a) [29] and suspension structure at supports (b) [30].
Table 2.1: Catenary system parameters [31]

<table>
<thead>
<tr>
<th></th>
<th>SYT7/0.9/8</th>
<th>SYT15/15</th>
<th>ST9.8/9.8</th>
<th>ST15/15</th>
</tr>
</thead>
<tbody>
<tr>
<td>Contact wire tension</td>
<td>9.8</td>
<td>15</td>
<td>9.8</td>
<td>15</td>
</tr>
<tr>
<td>(kN)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Catenary wire tension</td>
<td>7.0</td>
<td>15</td>
<td>9.8</td>
<td>15</td>
</tr>
<tr>
<td>(kN)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Span length (m)</td>
<td>60</td>
<td>60</td>
<td>60</td>
<td>60</td>
</tr>
<tr>
<td>Dropper spacing (m)</td>
<td>9</td>
<td>8.33</td>
<td>8.53</td>
<td>6</td>
</tr>
<tr>
<td>System Height (mm)</td>
<td>1300</td>
<td>1800</td>
<td>1550</td>
<td>1550</td>
</tr>
<tr>
<td>Stagger distance (mm)</td>
<td>±300</td>
<td>±300</td>
<td>±300</td>
<td>±300</td>
</tr>
<tr>
<td>Sag distance at mid-span (mm)</td>
<td>30</td>
<td>0</td>
<td>30</td>
<td>30</td>
</tr>
<tr>
<td>Max Speed (km/h)</td>
<td>200</td>
<td>250</td>
<td>180</td>
<td>220</td>
</tr>
</tbody>
</table>

2.2 Technical principles

The pantograph-catenary system is a coupled system with complex structures and the dynamic interaction between pantograph and catenary mainly depends on the design of the pantograph-catenary system as well as other factors, such as wind load, gradient, curvature and structural errors. In order to investigate the system and to derive a numerical model, the system is usually simplified into a pre-tensioned string, or the combination of some pre-tensioned strings and lumped masses under various working conditions, as shown in Figure 2.4, which allows the system to be numerically modeled with mathematical tools. Although the catenary is often modeled with beam elements with bending stiffness instead of strings in practice, the basic principles regarding the dynamic interaction in the pantograph-catenary system are still similar and give rise to dynamic phenomena as described below.

![Figure 2.4: The simplified model of the pantograph-catenary system.](image-url)
The speed of the propagating wave

The wave propagating on the catenary is excited by the moving pantograph. The wave on the catenary spreads from the contact point between pantograph and catenary forwards and backwards, and the pantograph moving along the catenary therefore has to confront the propagating wave excited by itself. Once the train speed reaches the speed of the propagating wave, the dynamic performance can significantly get decreased. The speed of the wave propagation on the pre-tensioned structure, $c$, can be approximated as [1]

$$c = \sqrt{\sigma/\gamma} = \sqrt{T_{CW}/m'_{CW}}$$

(2.1)

where $\sigma$ is the tensile stress, $\gamma$ is the mass density per length unit, $T_{CW}$ is the tensile force and $m'_{CW}$ is the mass per meter of the contact wire.

The reflection coefficient

The contact wire is assumed to be a pre-tensioned string, but there are a lot of necessary obstructers on the wire, i.e. clamps, steady arms and droppers, which make the mass distribution of the wire uneven. The traveling wave can be blocked and reflected by the uneven masses on the wire. The reflection coefficient is a value describing the relationship of amplitudes between the input wave and the reflected wave. The reflection coefficient caused by dropper is defined as [1]

$$r = 1/(1 + \frac{T_{CW}m'_{CW}}{\sqrt{T_{MW}m'_{MW}}})$$

(2.2)

where $T_{MW}$ is the tensile forces on the catenary wire, and $m'_{MW}$ is the mass per meter for the catenary wire.

Doppler factor

Since the vibrating source is a pantograph moving along the catenary, the excitation of one certain point on the catenary is always moving. In this case, the system shows the Doppler Effect, i.e. the change of oscillating frequency between the point on the wire and the pantograph. The Doppler factor, $\alpha$, which describes the Doppler Effect on the pantograph-catenary system, is defined as [1]

$$\alpha = (c - v)/(c + v)$$

(2.3)

where $c$ is the speed of propagating wave on the catenary and $v$ is the running speed of the pantograph.
The amplification coefficient

Reflections of the propagating waves by masses or other non-homogeneous sections on the contact wire can affect the wave propagation. The amplitude increases or decreases with a pantograph moving towards the reflected waves. The amplification coefficient, $\gamma$, shows how much of the contact force would be increased or decreased as the pantograph is running towards a reflected wave. It is defined as [1]

$$\gamma = \frac{r}{\alpha}$$

(2.4)

The limit speed on the catenary system

The limit speed, $v_a$, is the speed at which the amplification coefficient is equal to one, which means the amplitude of the oscillation on the catenary would gradually go to infinity when running above this speed limit on this system. It is defined as [1]

$$v_a = c \frac{1-r}{1+r}$$

(2.5)

The natural frequency of catenary

The catenary system has a large number of degrees of freedom (DOF) and can oscillate at numerous natural frequencies. As the catenary is suspended between equally spaced poles, it primarily exhibits symmetrical and anti-symmetrical oscillation modes. The first natural frequency, for anti-symmetrical oscillation, can be calculated as [1]

$$f_1 = \sqrt{\frac{T_{CW}+T_{MW}}{m_{CW}+m_{MW}}} / (2l)$$

(2.6)

and the second natural frequency, for symmetrical oscillation, is defined as

$$f_2 = \sqrt{\frac{H_{CW}+H_{MW}}{m'_{CW}+m'_{MW}}} / (2l + l_1)$$

(2.7)

where $l$ is the length of a span and $l_1$ is the distance between the two droppers near the supporting point.

Stiffness variation due to zig-zag suspension

To achieve relatively uniform wear on the contact strips on the pantograph to extend the service life, the zig-zag suspension is widely applied to all kinds of catenary systems, as shown in Figure 2. In this way, more even wear is achieved, but the shifting contact point on the pan-head leads to vertical stiffness variation in a span and some other influences,
like rotational inertia. Compared with the stiffness and wave propagation, the impact of the zig-zag suspension on the dynamic performance of the system is not significant. The vertical stiffness of the pan-head at the contact point in vertical direction can be approximated as [31]

\[ k_{\text{strip}} = k \left( \frac{L^2}{L^2 + x^2} \right) \]  (2.8)

where \( k \) is the vertical stiffness of the contact strip in the middle, which can be expressed as \((k_1 + k_2)/2\), \( L \) is the distance between two supporting points on a contact strip and \( x \) is the deviation distance of the contact point away from the contact strip center in the lateral direction.

### 2.3 Assessment

The decisive criterion for assessing the contact quality and in turn the quality of the energy transmission is the contact force between the contact strips of the pantograph and the contact wire of the catenary. Too low contact forces result in contact loss and too high contact force results in excessive wear. It is necessary to restrict the contact force within a certain limit during operation. In practice, it is very hard to evaluate the dynamic performance simply by the contact force only in time domain. Therefore, statistical analysis of the contact force is usually taken as the main method both for on-track test and for simulation, according to EN 50317 [32]. The key parameters to evaluate the dynamic behavior of the system [33] are:

- Mean contact force, \( M \),
- Standard deviation of contact force, \( \sigma \),
- Statistical maximum contact force, \( M + 3\sigma \),
- Statistical minimum contact force, \( M - 3\sigma \),
- Statistical occurrence of loss, the statistical minimum contact force below zero,
- Statistical occurrence of low contact force below specified safety margin.

For different systems, there are different limits of the statistical maximum and minimum contact force. Studies show that the mean contact force is mainly determined by the uplift force and the speed-related contribution. Therefore, for the mean contact force, there are target values of the mean contact force with respect to the running speed, such as \( M = 0.00097v^2 + 70 \) N [32]. Regarding the statistical value, the standard deviation should always be less than 30% of the target value.

In some cases, unacceptable high uplifts on the catenary occur in which the permissible maximum uplift relevant to operational safety at the support is exceeded, when the
pantograph passes. For other positions, this is not a problem, but the pan-head hits the steady arm or the steady arm hits other stationary structures when the uplift around the steady arms is too high. This can result in structural damage to the pantograph and the catenary equipment. The maximum uplift at the support is restricted by \( 50 + 0.00175v^2 \) according to EN 50317 [32].

**2.4 Testing**

The dynamic interaction between pantograph and catenary should be measured for the purpose of the performance assessment of the dynamic characteristics. With the development of technology, many detection methods have been introduced and some accurate results are possible to be acquired in a convenient and economical way. The key characteristics, such as the contact force between pantograph and catenary, the uplift of the contact wire, the dynamic characteristics of the pantograph, and the wear of contact wire, can be measured with different apparatuses.

**Measurement of contact force**

The contact force between pantograph and catenary is very hard to be directly measured. Therefore, the contact force is acquired indirectly. It is often measured separately; the supporting forces at the frame are measured by force transducers and the acceleration of the contact strips is measured by accelerometers [34]. The contact force at each contact strip of the pan-head can be written as

\[
F_{\text{contact}} = m_{\text{strip}} \times a + F_{\text{sensor1}} + F_{\text{sensor2}}
\]  

(2.9)

where \( m_{\text{strip}} \) is the mass of each contact strip, \( a \) is the acceleration of the contact strip, and \( F_{\text{sensor1}} \) and \( F_{\text{sensor2}} \) are the supporting forces measured by the force transducers.

![Force transducer and accelerometer](image)

Figure 2.5: Measurement of contact force.
Measurement of contact wire uplift and acceleration

The uplift or the acceleration on the contact wire is another key measure which can indicate the dynamic behaviour of the dynamic interaction between pantograph and catenary during operation. Furthermore, the uplift of the contact wire at the steady arms is a main criterion to evaluate the running safety. The uplift is measured by contact or non-contact sensors fixed to a stationary structure, such as registration arm and poles. The sensor records the motion of the contact wire at the corresponding point and sends out the data. The measuring point is usually located around the poles where is easy to be installed. [35]

Similarly, the acceleration can be recorded by an acceleration meter attached to the contact wire. The weight of the meter is kept as low as possible, otherwise the additional mass can affect the dynamic behavior. As there are a lots of influencing factors, i.e. structural errors and disturbance, which are hard to be reflected in simulation models, some key system parameters, like damping ratio and sliding friction, are acquired from measuring results.

Measurement of dynamic characteristics of pantograph

The dynamic characteristics of the pantographs is another important factor which directly determines the contact performance between pantograph and catenary. As the pantograph has a complex structure, it shows different response with respect to excitation, as shown in Figure 2.6. Frequency response analysis is usually used to determine the dynamic characteristics of a pantograph to derive the needed system parameter for simulation models. An example of frequency response functions of a pantograph is shown in Figure 2.7.

Figure 2.6: Test rig for the pantograph [36].
These parameters can then be obtained by comparing the correlation between the measured quantities and simulated results in the frequency domain. The pantograph is excited at different frequencies and the responses of the pantograph is recorded according to the oscillation applied. The dynamic characteristics of the pantograph can therefore be described by the measured frequency response function.

Figure 3.7: Modulus of frequency response function of pantograph, measured in the middle of contact strip of pantograph (black) and near the connection to the frame (red curve). [37]
3 Modelling and validation

As the interaction between pantograph and catenary is an important issue for railway operation relating to construction, maintenance, interoperability and design, dynamic testing should always be carried out to check the safety, reliability and feasibility of each pantograph-catenary combination. However, on-track tests are not only costly and time-consuming but can also be risky if the system is not fully validated. With the development of computer technology, it is possible to perform numerical simulations at manageable computational effort and many influencing factors can be taken into account. The numerical model allows for very detailed investigations, which are sometimes very hard or even impossible to do in a real test. Although numerical simulation is cost- and time-saving, successful simulation requires that the dynamics of the pantograph-catenary system are properly modelled and that the key parameters are in accordance with the real pantograph-catenary system.

The pantograph and the catenary are two independent systems coupled at the contact point. The simulation is aimed to establish the coupling between the partial models via the contact force and the position of the contact point. A suitable simulation of the dynamic behaviour and the interaction at the coupling point is required to correct results for the contact force and the vertical motion of the contact point.

3.1 Pantograph

There are many modeling methods to build the pantograph, i.e. analytical pantograph models, finite element models and low order model. In analytical method, the pantograph is built up with a mathematical model according to the geometry and material properties of the real pantograph, taking the bending of the frame, the vertical and angular movements into consideration. However, this method is seldom used today, because new calculation algorithms are required once there are small changes to the design of the pantograph. In finite element implementations, the pantograph model also follows the geometry and material properties of the real pantograph and is solved with the finite element method (FEM), which allows more degrees of freedom to be taken into account. However, there is very little improvement achieved while a lot of calculation effort is required. Therefore a low-order pantograph model is often used nowadays, either two-dimensional or three-dimensional models.

The pantograph is often simplified into substitute masses which are coupled to each other through springs and dampers as well as other elements if necessary. The oscillation behaviour of the system is described by second-order differential equations. The number
of equations is determined by the number of substitute masses and the number of degrees of freedom [1, 33, 38]. Low order models are often used, for example, a two-mass model as shown in Figure 3.1. The pantograph is discretized into the pan-head ($m_3$), the frame ($m_4$) and the additional masses on the pan-head ($m_1, m_2$). The pan-head is supported by two combinations of spring-damper elements and gaps at two supporting points. The frame connects to the moving base through a combination of friction slider and damper. The lateral stagger of the contact wire in the model causes contact point variation on the contact strip. Two translational degrees of freedom and one rotational degree of freedom are taken into account. The two main parts follow linear force laws around a certain operational height according to the fundamental kinematics.

![Diagram of pantograph model](image)

Figure 3.1: Two-mass model of pantograph [31].

### 3.2 Catenary

The catenary dynamics has been studied by many different methods, i.e. finite element method, analytical method, and modal analysis method. As the catenary is a large and complex structure, the model of the catenary does not take all detailed parts of the structure into consideration. In analytical models, the catenary is usually simplified with the combination of a pre-tensioned beam and lumped masses, and the dynamics of the catenary is mathematically solved based on the physical properties of the system. The analytical method cannot take many influencing factors and details of the structure into account and any modification to the system in the model is complicated. The modal analysis method is based on calculation of a number of eigen frequencies and eigen values of the catenary systems, but the boundary conditions are time-dependent as the pantograph is always moving. Nowadays, the finite element method (FEM), one of the approximation methods, is widely used in the investigation of the dynamics of the
pantograph-catenary system, which allows a high degree of freedom to be taken into account. It gives accurate solutions and allows modifications to be easily implemented. In the case of FEM, the catenary is subdivided into different elements, which are built and coupled in mathematical terms with respect to the mechanism of each part, and accurate solutions can be acquired for a wide range of applications. The influencing factors, such as non-linearity, damping, pre-sag, special sections and stagger, can easily be discussed. As the catenary is a long and thin structure, the contact wire is usually built up with a tensioned Euler-Bernoulli-Timoshenko beam elements. [1, 33, 38]

A catenary is a complex periodic structure. The catenary model described here is a three dimensional finite element model, which mainly consists of droppers, stitch wire, steady arms, contact wire and catenary wire. The system is assembled with the finite element method and the equations of motion can be written as

\[ M \ddot{x} + C \dot{x} + Kx = F \]  

(3.1)

where \( M \), \( C \) and \( K \) are global mass, damping and stiffness matrices respectively for the system, \( F \) the force vector and \( x \) the nodal displacement vector with the corresponding time derivatives. Proportional damping is introduced to form \( C \), which is given as a linear combination of the stiffness \( K \) and mass \( M \) and can be written as

\[ C = \alpha \cdot K + \beta \cdot M \]  

(3.2)

where \( \alpha \) and \( \beta \) are the proportional damping factors.

The catenary model is as shown in detail in Figure 2.2. The contact wire is modelled with 2-node Euler-Bernoulli beam elements, the catenary wire with truss elements. Dropper slackening, as shown in Figure 3.2, is one main reason for non-linear effects. Therefore, the droppers in the model are built up with uniaxial spar elements, which deform elastically under tension force and insulate the axial compression force. Lumped masses are introduced to model the clamps, which connect both contact wire and catenary wire to droppers. As the zig-zag suspension is taken into account, the steady arms, which support the contact wire and control the lateral stagger, are modelled with truss elements. Static loads in the longitudinal direction are applied on the two ends of both contact wire and catenary wire.
3.3 Contact

The interaction between pantograph and catenary is manifested at the contact point, i.e. the two sub-systems are also coupled at that point. So the model of the contact between pantograph and catenary is perhaps the most critical part of the model. There are several important factors affecting the whole system, such as wire irregularities, contact force, contact loss, aerodynamic disturbance, thermal effect, wear, and current conducting, all of which should be taken into account on different purposes. There are two main methods widely used. One method treats the contact as a rigid constraint with local equilibrium equations of Lagrange multipliers. The method requires a relatively complicated procedure to calculate the displacement of the contact point along the catenary and across the current collector. This may require a high computational effort and also result in mathematical problems, due to the discretization of the contacting bodies [1, 33, 38]. The other method relies on the use of the penalty method to approximately account for the constraints acting at the interface between pantograph and catenary.

To describe the contact between pantograph and catenary, the penalty method is used in this study to determine the contact force [15]. Two types of elements are used, one contact element applied on the contact strip of the pantograph and one target element applied on the full length of the contact wire. It forms a line/line contact pair. The contact force is applied only when the contact element on the contact strip penetrates the target element along the contact wire. The contact force $F_{contact}$ is therefore defined as

$$F_{contact} = K_n g \quad , \quad \text{if } g \leq 0$$

$$F_{contact} = 0 \quad , \quad \text{if } g > 0$$

where $K_n$ is the stiffness and $g$ is the magnitude of the gap between the contact element and the target element.
3.4 Validation

All validation should comply with EN 50318 [40]. In the process, the mean contact force from simulation should be within ±10% of the tolerance range of the mean contact force from on-track tests performed on the same system. The standard deviation should be within the range of ±20%.

The validation is performed on systems with and without stitch wire at running speeds up to 250 km/h. The difference in standard deviation, \( \sigma \), of the contact force between simulation and test results is shown in Table 3.1. It is concluded that the model used in this study fulfils the requirements according to EN 50318 in both single and double pantograph operation at speeds up to 250 km/h.

<table>
<thead>
<tr>
<th>System</th>
<th>Tension force (kN)</th>
<th>Stitch wire</th>
<th>Number of pantographs</th>
<th>( \Delta \sigma_1 (%) )</th>
<th>( \Delta \sigma_2 (%) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>ST 15/15</td>
<td>15</td>
<td>No</td>
<td>1</td>
<td>14</td>
<td>-</td>
</tr>
<tr>
<td>SYT 15/15</td>
<td>15</td>
<td>Yes</td>
<td>1</td>
<td>2</td>
<td>-</td>
</tr>
<tr>
<td>ST 15/15</td>
<td>15</td>
<td>No</td>
<td>2</td>
<td>8</td>
<td>7</td>
</tr>
<tr>
<td>SYT 15/15</td>
<td>15</td>
<td>Yes</td>
<td>2</td>
<td>16</td>
<td>8</td>
</tr>
</tbody>
</table>

Figure 3.3 shows a comparison between simulated and measured contact force on the Swedish SYT 7.0/9.8 catenary system. This is a relatively old and soft system that has been upgraded since the 1990s and is currently operated at speeds up to 200 km/h. The running tests were performed within the Green Train R&D program. A good agreement is found between test and simulation at speeds up to 280 km/h. For higher speeds, however, the results diverge, but that is far above 200 km/h which is the maximal operational speed.

Figure 3.3: Comparison between simulated (a) and measured (a) contact force for single pantograph operation on SYT 7.0/9.8 catenary system.
4 Possible measures to allow speed increase

At the beginning of the railway electrification, the dynamic load did not play an important role due to relatively low running speeds. These pantograph-catenary systems are both simple to install and easy and cheap to maintain. However, with the development of railway technology, operational speeds for most railway lines have significantly been increased, so that the dynamic interaction between pantograph and catenary has become one of the key issues which engineers who deal with system development and maintenance care about to ensure an uninterrupted, reliable, economical and safe operation.

Vertical stiffness variations and wave propagation in the railway catenary system cause high dynamic force variations in the contact between pantograph and catenary at high operating speeds. The large variation of dynamic force leads to low quality of current collection, increased mechanical wear, and electromagnetic interferences, as shown in Figure 4.1, and as already mentioned in the chapter before. To increase operational speed on an existing catenary system, technical upgrading on structures is usually required to keep the variation within an acceptable range. According to a number of studies, possible technical modifications are [1, 18, 35, 41-44]:

- Increasing the tension forces on the catenary system;
- Introducing a stitch wire or auxiliary wire into the catenary system;
- Introducing sag in the middle of a span of a catenary system;
- Reducing the mass of the pan-head to reduce the dynamic variation of the contact force;
- Introducing an active pantograph to improve the dynamic performance.

Figure 4.1: Worn contact strips [45] (a) and arcing during working [39] (b).

All the measures mentioned above require either modifying the structure of the catenary system or improving the dynamic behaviour of the pantograph. For newly built lines, all of these methods can easily be employed. The implementation of most of these measures on existing lines, however, does not only need large investments but also long out-of-service times to upgrade the existing catenary system for a higher operational
speed. The following sections discuss how the measures help to improve the dynamic performance for high speeds.

4.1 Reduction of stiffness variation

The catenary is suspended at poles or other similar designs. The distance between the supports directly determines the costs of the construction as well as the vertical stiffness in a span. The stiffness variation in a span also depends on both the tensile force applied to the wires and the structure of the design. As the support of the catenary is not continuous, the stiffness is always low in mid-spans and high around the supporting points. Figure 4.2 compares the vertical stiffness of six types of catenary designs in Sweden. The vertical stiffness variation is one of the major sources which can cause high dynamic variation in the contact force between pantograph and catenary at high operating speeds.

![Contact wire elasticity](image.png)

**Figure 4.2:** Comparison of vertical stiffness of six types of Swedish catenary designs [34].

In order to reduce stiffness variation without increasing tensile force, various designs like stitch wire and compound catenary are used as shown in Figure 4.3. The additional stitch wire makes the vertical stiffness of the contact wire smoother around supporting poles and the auxiliary wire in the compound catenary makes the contact wire better suspended than a simple catenary. The improvement of the stiffness variation contributed by the stitch wire can be seen in Figure 4.2. Since the compound catenary is more complex than the stitch wire catenary, the stitch wire catenary is more popular worldwide.
Actually, no matter what kind of design is applied, the vertical stiffness variation inevitably exists and always affects the dynamic performance.

![Diagram](image)

(a)

![Diagram](image)

(b)

![Diagram](image)

(c)

Figure 4.3: Suspension structures: simple catenary system (a), stitch wire catenary system (b) and compound catenary system (c). [39]

### 4.2 Tensile force increase

In order to increase the operational speed of a certain system, the most obvious method is to increase the tensile forces on the catenary, which both reduces the vertical stiffness variation and increases the speed of the propagating wave on the catenary. For high-speed catenary systems, high tensile force designs are often applied. For the in Sweden widely used catenary system SYT 7.0/9.8, the operational speed is 200 km/h, the tensile forces are 7.0 kN and 9.8 kN on the catenary wire and contact wire respectively. In the standardized high-speed catenary Re 330 in Germany, capable of 350 km/h, the tensile forces are 21 kN and 27 kN correspondingly. In the speed-record run in 2007, a speed of 574 km/h was achieved by SNCF and the tensile forces on the tested catenary system was increased to 40 kN. Table 4.1 shows the tensile forces of some catenary systems.

Although high tensile forces on the catenary are desirable, regarding the material property of the contact wire and the safety issue, the tensile forces cannot go to infinity due to the maximum permissible stress and the fatigue under the alternating force. Nowadays, some wires of catenary are made of alloy materials and some designs which have hard core in the wire are adopted to help the contact wire and catenary to cope with high tensile stress to achieve a high operational speed on a certain catenary system.
Table 4.1: Tensile force applied to high-speed catenary systems [46]

<table>
<thead>
<tr>
<th>Country</th>
<th>System</th>
<th>Operational speed</th>
<th>Tensile force on contact wire</th>
<th>Tensile force on catenary wire</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sweden</td>
<td>SYT 15/15</td>
<td>250</td>
<td>15 kN</td>
<td>15 kN</td>
</tr>
<tr>
<td>Germany</td>
<td>Re 330</td>
<td>330</td>
<td>27 kN</td>
<td>21 kN</td>
</tr>
<tr>
<td>France</td>
<td>Atlantique</td>
<td>320</td>
<td>20 kN</td>
<td>14 kN</td>
</tr>
<tr>
<td>Italy</td>
<td>Rom-Neapel</td>
<td>300</td>
<td>20 kN</td>
<td>16.25 kN</td>
</tr>
<tr>
<td>Spain</td>
<td>Madrid-Lerida</td>
<td>350</td>
<td>31.5 kN</td>
<td>15.75 kN</td>
</tr>
<tr>
<td>Japan*</td>
<td>Osaka-Hakata</td>
<td>300</td>
<td>19.6 kN</td>
<td>24.5 kN</td>
</tr>
<tr>
<td>China</td>
<td>Beijing-Shanghai</td>
<td>350</td>
<td>31.5 kN</td>
<td>20 kN</td>
</tr>
</tbody>
</table>

* Compound catenary system: the tensile force on the auxiliary wire is 14.7 kN.

4.3 Pre-sag

The stiffness variation in every span is periodically repeated, high around supporters and low in mid-span. To compensate for the stiffness variation, pre-sag of the contact wire is introduced in some designs by slightly adjusting the length of each dropper in a span, as shown in Figure 4.4.

![Figure 4.4: Slight sag in mid-span [18]](image-url)
If there is no pre-sag in the middle span, the pantograph would lift the contact wire to a greater distance around mid-span where the vertical stiffness is low. The pre-sag enables the contact wire to be lifted to a relatively constant height with respect to the rail head, so that the vertical motion of the pantograph can be slightly restricted and a better dynamic performance can be expected, as shown in Figure 4.5. However, the improvement of dynamic behaviour caused by the pre-sag heavily depends on the operational condition of the pantograph, which means a certain pre-sag can only improve the dynamic performance at a certain speed but deteriorate it at other speeds. In practice, the pre-sag should be optimized with respect to the type of system to achieve a good dynamic behavior. However, for high-speed railways, the improvement due to the pre-sag is very little and in some cases, pre-sag even shows some negative effects. Therefore, the use of pre-sag is very rare in the high-speed catenary systems whose operational speeds are over 300 km/h.

![Figure 4.5: Contact force in an on-track test in a section with and without pre-sag [18].](image)

### 4.4 Dropper with damping

All catenary systems have very low damping, so the oscillations in the systems and in turn the reflected wave are hard to be reduced. The low damping significantly affects the dynamic performance, especially in multi-pantograph operation. In order to increase damping in the system, rubber damping droppers or friction damping droppers are introduced into some designs, as shown in Figure 4.6. The application can effectively reduce the amplitude of the high-frequency oscillation of the contact wire, so that arcing and wear on the contact wire can be reduced.
4.5 Actively controlled pantograph

The pantograph is a well-designed equipment to support the contact strips sliding against the contact wire of the catenary. As the pan-head can be regarded as un-sprung mass, which contributes a lot to the dynamic load, for high-speed pantographs, the mass of the pan-head is often reduced to a very low value. There is another option to enable the existing system to cope with a higher speed – an actively controlled pantograph with hydraulically servo-actuator, which allows the pantograph to adjust itself to cater for the stiffness variation. With the development of control strategies and the application of fast controllers, the use of actively controlled pantographs becomes possible.

An active control system detects the changes of the contact force and makes the system compatible with these changes to reduce contact loss and keep the contact force relatively stable. Although there are many control strategies, the aim of all the strategies is to keep the contact force as constant as possible. To achieve the best dynamic performance, there are many studies on the application of control strategies to pantograph-catenary systems and the layout of the controller. Figure 4.7 shows an example of the scheme of PID control by means of a β-Newmark scheme. To meet the safety requirement during running, the current transmission has to be guaranteed by the passive structure even if the active control system fails working.

Figure 4.6: Applications of rubber damping dropper [47].

Figure 4.7: Simulink model of a system with PID control [41].
5 Multi-pantograph operation

Normally, each locomotive or EMU unit uses only one single pantograph during operation. However, when there are some special demands or requirements, i.e. an additional locomotive to provide sufficient power or coupled EMU trainsets to adapt to daily or seasonal passenger-flow variation, two or even more pantographs can be used in contact with the catenary at the same time, as shown in Figure 5.1. The purpose of multi-pantograph operation is not only to provide the necessary energy but also to work as a redundant system, i.e. if any incident occurs with one of the pantographs, the other one is able to keep the trainset running without the need to stop the transport service. [1, 15, 16]

![Figure 5.1: The Swedish Regina train with multi-pantograph operation [49].](image)

Although multi-pantograph operation is a convenient and efficient way to operate rolling stock and use railway infrastructure, there are many differences compared to single-pantograph operation in the same condition. At low speeds, the multi-pantograph operation does not differ very much from single-pantograph operation, but the dynamic influence between pantographs dramatically increases with speed. The trailing pantograph becomes more sensitive and vulnerable than the leading pantograph, and the dynamic behavior of the trailing pantograph can be totally changed. In any case, the multi-pantograph operation raises problems that do not occur when using a single pantograph to supply the power to the trainsets.

5.1 Spacing distance

Under multi-pantograph operation, the trailing pantograph has to travel through a catenary, which has been heavily excited by the leading pantograph. So the dynamic behavior of the trailing pantograph usually gets worse than that of the leading pantograph. On the other hand, the leading pantograph is to some extent influenced by the propagating wave caused by the trailing pantograph, which means that the leading pantograph can also be significantly influenced when the spacing distance is too short. Figure 5.2 shows the contact forces in two-pantograph operation. We can see that at 40 m spacing distance,
there is contact loss appearing on the trailing pantograph and some positions with very low contact force on the leading pantograph can be detected. Generally speaking, the longer the spacing distance between pantographs, the less influence between pantographs. According to test results, when the time delay determined by pantograph spacing distance and train speed is close to the period of the first natural frequency of the catenary, the probability of contact loss for the trailing pantograph can be high even for relatively low speed, causing the formation of electrical arcs. In practice, to sustain the quality of current collection and avoid risking operational safety, there are today strict regulations, which limit the minimum spacing distance between pantographs with respect to each type of catenary system.

![Figure 5.2: Contact forces from simulation as a function of traveling distance under two-pantograph operation at 300 km/h: spacing at 40 m (a) and 120 m (b) [50].](image)

### 5.2 Different catenary systems

Multi-pantograph operation on different catenary systems can give very different dynamic performance. Figure 5.3 shows the dynamic performance on two different catenary systems: SYT 7.0/9.8 for a maximum speed of 200 km/h and SYT 15/15 for 250 km/h. As we can see, the high-speed catenary is generally more suitable for multi-pantograph operation and the dynamic performance does not get decreased very much with the number of pantographs in use increasing. For the catenary systems with high tensile forces, the standard deviations can significantly be restricted under the same working conditions compared with soft catenary systems, so it can be concluded that the dynamic performance is heavily dependent on the design of the catenary system. By comparing the results in the same catenary system, it shows that the number of pantographs in use does not affect the system very much.
Figure 5.3: Standard deviation of contact force as a function of running speed on two catenary systems and five spacing distances: the second pantograph in two-pantograph operation (a) and the third pantograph in three-pantograph operation (b).

5.3 Preload differentiation

There are some studies on how slight differences of working conditions affect the dynamic behaviour of the system [27]. To show the effectiveness of some measures, a pantograph preload differentiation is analyzed with two pantographs at a distance of 80 m. Two kinds of simulation models are employed.

In this study, the uplift preload on the leading pantograph is reduced while the trailing pantograph uses two amounts of uplift preload. As shown in Figure 5.4, the standard deviation of the contact force of the trailing pantograph gets reduced with the preload on the leading pantograph decreasing. However, as the mean contact force is directly determined by the uplift preload on the pantograph, there is a limit to the mean contact force that the standard deviation must always be less than 30% of the mean contact force, $\sigma_l < 0.3Fm_l$, according to TSI standard. Under normal working conditions, when the uplift force on one of the pantographs is reduced to a very low value, contact loss appears and the dynamic performance of the corresponding pantograph can get deteriorated. Therefore, even though the uplift force reduction of the leading pantograph can benefit
the trailing pantograph to some extent, this measure can only be applied to very limited extent in reality under normal conditions.

Figure 5.4: Contact force standard deviation of trailing pantograph as a function of leading pantograph mean force. Speed 250 km/h, distance between pantographs 80 m. The dashed lines are for KTH results and solid lines for POLIMI results [27].
6 Summary of appended papers

6.1 Paper A

In this paper, in order to investigate whether it is possible or not to run future high-speed trains at speeds up to 250 km/h and with up to three pantographs at short spacing distances on existing catenary systems, computational analysis of the dynamic interaction between pantograph and catenary is carried out based on a 3D finite element (FE) pantograph-catenary model.

Some technical details of the 3D model are given, which can show the pan-head stiffness variation due to the zig-zag suspension of the catenary. The model is validated by comparing simulation results with other results, such as from on-track tests and simulations with a 2D model. After analyzing the contact force with pantograph spacing distances between 60m and 120 m, and with up to three pantographs, the relationship between dynamic performance and parameters, such as the distance of pantograph spacing, the number of pantographs in use and the position of the pantographs in the operation is investigated to better understand the multi-pantograph system. Finally, the key parameters which heavily influence the performance of flexible train sets operating with multiple pantograph are addressed.

The simulation results show that the spacing distance between pantographs is the most critical factor that affects the whole system within multi-pantograph operation. A properly selected spacing distance between pantographs and a suitable system for the desired span of running speeds can to some extent contribute to an improvement of the running condition for the trailing pantographs. It is also shown that a pantograph is little influenced by the one after it, while all pantographs ahead of it heavily influence a trailing pantograph. The mean contact forces are neither sensitive to the number of pantographs in the system nor the spacing distances between pantographs. The results show that it is possible to operate coupled trainsets with three pantographs and still achieve a good performance of current collection.

6.2 Paper B

According to the conclusions in Paper A, it is not necessary to avoid multi-pantograph operation or to set the spacing distance very high to reduce the influence between pantographs. To further investigate how pantographs affect each other in multi-pantograph operation, based on the numerical model introduced in Paper A, another numerical study on two-pantograph operation at short spacing distance between
pantographs, 30 m to 60 m, is carried out, where the influence between pantographs is significant and obvious.

The results show that the leading pantograph generally works better than the trailing pantograph, but at some certain spacing distances, the trailing pantograph performs not only better than the leading pantograph but also better than a single-pantograph operating at lower speed. To understand the phenomenon, this paper compares the contact forces and the response of points on the contact wire to passing pantographs under various conditions. Two main effects, which can lead to the improvement, are found: the leading pantograph exciting the catenary in a favorable way to improve the performance of the trailing pantograph and the wave interference between two pantographs helping to build up a favorable running condition for the trailing pantograph.

Compared to the costly and time-consuming methods to increase operational speed that have been mentioned in Chapter 4, an improvement of the dynamic behaviour acquired without any significant structural changes to the existing system is interesting and desirable. In order to take advantage of these two positive phenomena for high-speed operation and avoid excessive wear caused by the leading pantograph, the paper suggests that the leading pantograph can works as an auxiliary pantograph which does not conduct any electric current to achieve a better the dynamic performance for the trailing pantograph.

### 6.3 Paper C

Paper C is an extension paper of Paper B. This paper investigates the influences between pantographs in two-pantograph operation at short spacing distances. However, the results indicate that less than 15% of increase in speed can be achieved in the most favorable condition with help of the two positive effects explained above. To achieve further improvement of the dynamic performance at even higher speeds, this paper investigates the dynamic performance of the system with contact force reduction on the leading pantograph. Furthermore, we have carried out a brief parametric study on system parameter deviations and various system damping ratios to check the sensitivity and the feasibility of the auxiliary pantograph solution. Based on all the investigations, this paper makes proposals for running speed increase on existing catenary systems under auxiliary pantograph operation and suggestions for future studies on auxiliary pantograph operation.

Under these idealistic running conditions, this paper proposes that the leading pantograph with optimized uplift force can excite the catenary more properly and
therefore further help the trailing pantograph to improve dynamic performance at higher speeds.

The maximum uplift at steady arms exceeds the limit value at high speeds and may lead to collision between steady arm and pan-head. This can be avoided by methods, like increasing the clearances in the steady arm structure or the suspension structure, and even reducing the static uplift force a little bit at high speeds. The results show that the dynamic performance of the system is not very sensitive to a small deviations of some key parameters. Although the system damping affects the dynamic performance, the two positive effects are still working even if the system damping is changed significantly. It seems to be feasible to increase the operational speed on the soft Swedish catenary system, SYT 7.0/9.8, by 30% with the measures proposed.
7 Conclusions and future work

7.1 Conclusions

The purpose of this licentiate study is to investigate the dynamic behaviour of the multi-pantograph system and to better understand the relationship between the influencing factors and the resultant performance in order to meet the demand that more short trainsets can use three or even more pantographs and increase the operational speed on the existing system. The work includes studies on the structures and the dynamics of the pantograph-catenary systems, modelling and testing methods, dynamic behaviour of multi-pantograph systems, and possible methods to increase operational speed. All numerical simulations were performed in a 3D finite element (FE) pantograph-catenary model.

With the fast development of railways, it is possible to achieve an operational speed of 350 km/h or even higher on newly built lines, but there is also a demand for an increase in speed on existing lines. Technical upgrading is usually required, but the implementation does not only need large investments, but it also requires long out-of-service times. Beside the study on multi-pantograph operation, this work proposes technical solutions to achieve a speed increase on existing pantograph-catenary systems without significant changes to the existing designs.

In the study, it was found that the spacing distance between pantographs is the most critical factor that affects the whole system within a multi-pantograph operation. A pantograph is less influenced by the one after it, while a trailing pantograph is heavily influenced by all pantographs ahead of it. The mean contact force in different systems operating with multiple pantographs is not sensitive to the number of pantographs in use and the spacing distances between pantographs.

It was also found that in multiple pantograph operation, the leading pantograph can sometimes help the trailing pantograph to improve the dynamic performance if the spacing distance between pantographs is set properly. Two effects which heavily influence the dynamic performance were found: the leading pantograph exciting the catenary in a favourable way to improve the performance of the trailing pantograph and the wave interference between two pantographs helping to build up a favourable running condition for the trailing pantograph. In order to avoid deterioration of the dynamic performance at higher speeds and significant wear caused by the leading pantograph, a concept of an auxiliary pantograph is proposed.

It is also found that although the multi-pantograph system is not actively controlled, the auxiliary pantograph can to some extent manipulate the oscillation on the catenary catering for the working pantograph by adjusting the uplift force applied to the auxiliary pantograph. The auxiliary pantograph system is not very sensitive to small deviations of some parameters and the wide range of damping ratios applied.
7.2 Future work

In general, this study was performed under idealistic and simplified working conditions, many possible influencing factors need to be individually investigated according to the properties of a real system. In the future, more influencing factors, such as curvatures, disturbances and structural errors, will be taken into consideration and further parametric studies will be performed to help to achieve speed increase on existing lines. Furthermore, more investigations of the relationship between the response of the catenary after pantograph passing-by and some key parameters, i.e. pantograph spacing distances and running speeds, need to be compared with the results from tests to validate the positive effects found in the study. After full validation of the concept of the auxiliary pantograph, on-track tests are needed, which would allow further development of auxiliary pantograph.
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