Measures to Enhance the Dynamic Performance of Railway Catenaries

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Doctoral Thesis in Vehicle and Maritime Engineering

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Preface

The work presented in this thesis was performed between September 2013 and June 2017 at the Department of Aeronautical and Vehicle Engineering at KTH Royal Institute of Technology in Stockholm, Sweden.

It was mainly supported by KTH Royal Institute of Technology and China Scholarship Council, and partly by Swedish Transport Administration (Trafikverket), Bombardier Transportation and Schunk group. I would like to thank my main supervisor Prof. Sebastian Stichel in particular for guiding and inspiring me to explore the unknown world. I would like to give special thanks to my co-supervisors, Dr. Per-Anders Jönsson and Prof. Anders Rønnquist, for sharing their knowledge with me and helping me to solve every problem during my study. In addition, I appreciate Prof. Mats Berg for his kind help on every aspect during my PhD study.

I am grateful for the support from all other colleges in our unit: Carlos, Alireza, Saeed, Tomas, Yuyi, Weiyuan, Visakh as well as all the former colleges at the unit. I also give my thanks to Leping Feng and Petter Nåvik for helpful and fruitful discussions. In addition, I would like to thank the small Chinese community at my department at KTH and all my former colleges in China Academy of Railway Sciences.

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

Stockholm, June 2017

Zhendong LIU

劉振東
“滴水之恩，涌泉相报”
Abstract

The pantograph-catenary system is used in railways to transfer electric power from the stationary infrastructure to the moving trainset. As the pantograph slides against the catenary, the contact between the two surfaces is not stable due to stiffness variation, propagating wave and other environmental perturbation, especially at high speeds or in multi-pantograph operation. Heavy oscillation can result in poor power-transmission quality, electromagnetic interference, severe wear or even structural damage. Therefore, the pantograph-catenary dynamics has become one of the key issues which limits the maximum operational speed and determines the maintenance cost. There are many types of catenary systems developed in Sweden, which are relatively soft and sensitive compared with the systems used in other countries. They work well at low operational speed and have strict limitations to multi-pantograph operation. Although it is possible to achieve an operational speed of 350 km/h on newly-built high-speed lines, there is still a large demand for higher operational speed and more capacity on the existing lines.

Many researchers and engineers have made progress to improve the dynamic performance of pantograph-catenary systems. From the research aspect, many numerical models have been built up to better demonstrate the dynamics of the pantograph-catenary system and to unveil the key influencing factors. There have also been many engineering applications developed in recent years. From the catenary aspect, high-tensile loads on the catenary and low-stiffness-variation designs are widely used to improve the dynamic performance. From the pantograph aspect, aerodynamic-friendly designs and active-control technique contribute to the development of high-speed pantograph. All these methods to upgrade the existing systems need not only large investment but also long suspension of the service. Considering the large scale and the heavy service duty of the existing railway lines, it becomes almost impossible to completely upgrade the existing pantograph-catenary systems. Therefore, it is necessary to find practical and efficient methods to exploit the potentials of the existing systems to enhance their dynamic performances.

In response, this thesis investigates the dynamic behaviour of the existing Swedish pantograph-catenary systems and proposes methods for better usage of the existing systems. A numerical study on multi-pantograph operation is performed and the relationships between dynamic performance and some key parameters are established. By studying the multi-pantograph operation at short spacing distance between pantographs, a method to use the leading pantograph as auxiliary pantograph is proposed aiming to increase the operational speed on the soft catenary system. To ensure operational safety in abnormal conditions, numerical studies on pantograph raising/lowering processes and in catenary overlap sections are performed. By studying the influence of the catenary lumped-mass on the dynamic performance, it shows that it is not necessary to avoid the lumped-masses on the catenary. It is even possible to implement some artificial tuned-masses on the catenary for dynamic optimization.
**Keywords:** numerical study, pantograph-catenary interaction, soft catenary system, multi-pantograph operation, auxiliary-pantograph operation, tuned-mass application.
Sammanfattning


Som svar undersöker denna avhandling de dynamiska beteenden hos befintliga strömavtagare-kontaktledningssystem och föreslår metoder för bättre användning av befintliga system. En numerisk studie om multi-strömavtagardrift utförs och förhållanden mellan dynamisk prestanda och några nyckelparametrar undersöks. Efter att ha studerad fler-strömavtagardrift med kort avstånd mellan strömavtagare, föreslås en metod för att använda den ledande strömavtagaren som hjälpsströmavtagare för att öka driftshastigheten på det mjuka kontaktledningssystemet. För att säkerställa driftssäkerheten vid onormala förhållanden, utförs numeriska studier på höjnings- och sänkningsoperationen av strömavtagare och i överlappningen av kontaktledningssektioner. Genom att studera inverkan av punkt-massor på den dynamiska prestandan visar det sig att det inte är nödvändigt att alltid undvika den massan...
på kontaktledningsystemet och det är möjligt att använda vissa konstgjorda massor på kontaktledningsystemet för att optimera det dynamiska beteendet.

**Nyckelord:** numerisk studie, strömvattagare-kontaktledningssystem, fler-strömvattagardrift, mjukt kontaktledningssystem, extraströmvattagare, avstämt masssystem.
**Dissertation**

This thesis consists of a summary of the present work and a collection of the following appended papers:

**Paper A**

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

**Paper B**

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

**Paper C**

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

**Paper D**

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

**Paper E**

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

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

Paper G
Zhendong Liu, Sebastian Stichel and Anders Rønnquist, ‘Application of tuned-mass system on railway catenary for dynamic improvement’, Submitted to journal publication.

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

Publication and presentations not included in the thesis:


Thesis contribution

This thesis investigates the dynamic behaviour of railway pantograph-catenary systems in order to improve their dynamic performance and increase the operational capacity. The thesis contributes to the present research field as follows:

- A literature survey with regard to multi-pantograph operation has been carried out. The relationships between dynamic performance and some key parameters, e.g. the number of pantographs in use, operational speed and the position of the pantographs, are studied and some key factors which limit the operability in multi-pantograph operation are found.

- By studying the multi-pantograph operation at short spacing distance between pantographs, it is found that the dynamic performance of the trailing pantograph can be significantly improved or even qualified for a higher speed just by optimizing the spacing distance between pantographs. A method to increase the operation of the soft catenary system, i.e. auxiliary-pantograph operation, is proposed.

- To implement the auxiliary-pantograph operation, the phenomena in two-pantograph operation are studied and two positive effects which can lead to improvement are found. A small uplift reduction is suggested to further benefit the main pantograph. It shows that auxiliary-pantograph operation is an applicable method to enhance the operational capability of the existing catenary systems without much modification.

- To ensure operational safety in abnormal condition, a numerical study on the pantograph raising/lowering process in multi-pantograph operation is performed. The movement of the pantograph during raising/lowering is modeled by the gradient of a guiding slide. It shows that the operation of the leading pantograph should be careful to avoid disturbance, especially at short spacing distance and high speeds.

- To improve the dynamic performance of the soft catenary system, a numerical study on catenary overlap section, a special catenary section, is performed. The operational speed, zig-zag suspension, wire gradient and damping ratio are discussed. It shows that the wire gradient is a very important factor in keeping a smooth transition and some modifications should be implemented to increase operational speed of an existing catenary.

- By studying the influence of the lumped-mass distribution on the dynamic performance of the catenary system, it shows that it is not necessary to always keep the clamps and fittings on the catenary small and light. Improvement can be achieved if the lumped-mass is applied at some favourable positions.

- To let the existing pantograph-catenary system work better and overcome some difficulties in reality, an artificial tuned-mass system on the catenary is proposed. It shows that an increase or decrease of the contact force can occur at the positions as needed when the weight of the mass, the applied position and the elasticity of connection are well-designed. The working mechanism of the tuned-mass system is addressed.
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1 Introduction

The railway pantograph-catenary system is used to continuously transfer the electric power from the stationary structure to the running trainset. Although there are many other designs able to perform similar tasks, e.g. third rail/contact shoe and trolley pole/overhead line, they are not used in railway system due to mechanical limitations and safety concerns. The pantograph-catenary system is an elaborate design which can ensure good quality of electricity transmission at relatively high speeds. As the name implies, the pantograph-catenary system contains two sub-systems, as shown in Figure 1.1, the pantograph, mounted on the roof of trainset and the catenary, the overhead power line suspended above the track. The electric current is collected by the pantograph from the catenary and returned through the train wheels back to the rails. As the rails and wheels are always in good contact during operation, the contact between pantograph and catenary becomes one of the key issues for the reliability of railway operation [1-3].

![Figure 1.1: Sketch of pantograph-catenary system [3].](image)

The pantograph is an articulated structure, which consists of pan-head structure and supporting frame structure, as shown in Figure 1.2. The supporting frame is powered by the pneumatic cylinder on the base and is vertically raised up from the folded position to a certain range of working height while pushing the pan-head against the catenary with a roughly constant uplift force. The pan-head has enough width to cover all possible positions of the catenary in the lateral direction. To sustain a good contact between the two sliding surfaces, the pan-head is well suspended and the contact strips are usually mounted on the top of the pan-head to withstand wear. They are replaced during maintenance once the wear exceeds technical limitation. To minimize the wear between the two sliding surfaces, the contact strips are usually made of carbon due to its good conductivity, low wear rate and low friction coefficient against copper. Although carbon can self-lubricate the surfaces, it is a brittle material. To avoid the broken strip tearing down the catenary in case of system failure, the carbon contact strip is today made into a
hollow structure connected to the pneumatic pipe. If there is a crack on the carbon strip, leakage happens to the pneumatic system and the pantograph can therefore be automatically lowered. Although there are many pantograph variations with different shapes and sizes across the world, the main function and the fundamental structure are quite similar.

Figure 1.2: Example of railway pantograph [4].

The catenary is a well-suspended overhead power line above the track, as shown in Figure 1.3. Basically, the catenary consists of contact wire, catenary wire (messenger wire), droppers connecting the contact wire to the catenary wire and supporting, and suspension structures at the poles. The contact wire is made of copper or copper alloy due to the good electric conductivity of copper and its oxidized layer. Because of gravity, the wires cannot keep level by themselves, so the contact wire, directly in contact with the pantograph, is positioned through droppers in different lengths to the catenary wire to keep level. At the poles, the weight of the system is supported from the catenary wire by cantilevers. To avoid making notches on the pantograph during sliding, a zig-zag suspension is applied at the poles, as shown in Figure 1.4, where the steady arms pull or push the contact wire off the central line. From the investment aspect, the spacing distance between supporting poles should be built as long as possible, but in reality there are some technical limitations which restrict the implementation of long span design. To connect different components for supporting and electric reasons, there are many types of clamps and fittings used in the catenary system, as shown in Figure 1.5. Since the clamps and other fittings are additional masses attached to the wire, they are normally made light and small to avoid introducing disturbances. There are many different designs of the contact wire regarding shape and size of their cross-sections, but there are always two grooves on
the upper part of the contact wire which are used to fix the clamps and to avoid structural interference between the clamps and the passing pantograph. In reality, both the contact wire and catenary wire are pre-tensioned by the tensioning devices, which allows slight movement caused by the thermal expansion while sustaining a constant tensile load. Because of tensile force retention on the wires and electric concerns, the entire catenary is divided into many individual tensioning sections. To keep a smooth shift for the passing pantograph from one tensioning section to another tensioning section, there are always some overlaps between two neighboring tensioning sections, as shown in Figure 1.6. For different systems, the lengths and gradients of the overlap section vary a lot. There are many types of catenary systems with respect to different considerations, but the main structures of the catenary systems are almost the same.

Figure 1.3: Components of railway catenary [3].

Figure 1.4: Zig-zag suspension of railway catenary: (a) push-off structure and (b) pull-off structure [3].
The contact between pantograph and catenary is very important for the stability and safety of railway operation. In the most extreme condition, the pantograph-catenary system has to cope with an electric load of 27 kV and up to 1000 A, and a relative sliding speed of more than 100 m/s. As the pantograph is sliding against the catenary rather than fixed to it, the pantograph is designed to closely follow the movement of the catenary and the catenary is supposed to maintain a smooth targeting surface. Even though the geometry of the contact wire can be built perfectly levelled, the catenary is not continuously supported, so there is always vertical stiffness variation in longitudinal direction within each span, as shown in Figure 1.7. The pantograph sliding along the catenary therefore excite oscillations on the catenary. Due to the string-like structure of the catenary, the oscillations spread along the catenary and deteriorate the contact. Furthermore, the wave reflection, structural errors and environmental disturbances make the working conditions worse and more complicated. The oscillation gets significantly increased with speed. If they are not suppressed, the poor dynamic performance would lead to bad quality of power transition, excessive wear on the contacting surfaces, electromagnetic interferences to the environment and even structural damages. Today the pantograph-catenary dynamics has become one of the major factors, which limits the operational speed of railway lines and determines the service life of some key components. [1, 7]

The dynamics of the pantograph-catenary system is a big concern for both system designers and infrastructure operators. In recent years, many numerical studies have been carried and much progress has been made aiming for higher operational speed, lower maintenance cost, higher reliability and more flexibility. Many researchers have paid a lot of effort to correctly model the dynamics of the pantograph-catenary system [8-16]. Nåvik and Zou identified the dynamic system damping of the catenary system [17-18].
Collina and Pombo investigated the impact of catenary irregularity and pantograph suspension on the current collection [19-20]. Kim studied the influence of span length and static uplift force [21]. Song studied the stochastic wind effect [22]. Pombo, Li, Bocciolone and Noger analyzed the influence of aerodynamics [23-26]. Suzuki and Mitsuru tried to optimize the pantograph to reduce noise emission [27-28]. Rønnquist used the frequency-analysis method to evaluate the upgrade of a catenary [29]. Wu and Collina studied the application of an actively controlled pantograph for high-speed operation [30-31]. Pombo looked at the contact behavior at different positions and took environmental and track-originated perturbations into consideration [32]. Cho investigated the influence of contact wire pre-sag on the dynamics [33]. Zhai discussed the influence of vibration from car body on the system [34]. Ding and Zhang showed the friction and wear behaviour between pantograph and catenary [35]. Collina developed a model to predict wear [36]. Pombo, Zhang, Manabe and Drugge did many studies on multi-pantograph operation [37-40]. Harell and Drugge investigated the dynamic behavior of the pantograph-catenary system within special sections [40]. Bucca studied the influence of pantograph preload [41]. Tieri, Poetsch, Sanchez-Rebollo and Balestrino suggested using active control method to improve the dynamic performance [42-45]. Jerrelind studied the application of overhead system for road traffic [46]. From the engineering aspect, now it is possible to operate trains at 350 km/h on some newly-built high-speed lines and even 574 km/h during trials [47], and newly-designed pantographs can significantly reduce noise emissions and are not sensible to environmental disturbances [28].

![Figure 1.7: Vertical stiffness variation of four types of Swedish catenary systems](image)

The main railway lines in Sweden were electrified in the beginning of 20th century, and many types of catenary systems have been developed since then, as listed in Table 1.
Compared with the systems in other countries, they are relatively low-tensioned, which leads to large stiffness variations and low critical speeds. The operational speed is seriously limited and the service life of some key components is shortened. In addition, since Sweden is not a densely populated country, to efficiently use rolling stock and infrastructure, multi-pantograph operation is widely adopted. The pantographs can therefore significantly influence each other and often cannot work as well as single-pantograph operation. In some cases, it is still impossible for some coupled trains to run at the full speed as designed even though the spacing distance between pantographs is set as far as 160 m. For the newly-built lines, they can directly go for advanced catenary systems to overcome these limitations. However, as upgrading is not only costly but also time-consuming, it is almost impossible to completely upgrade the large existing railway networks considering the heavy work duty of the existing lines. However, for the existing systems, not only in Sweden but also elsewhere, there are still large demands for speed increase, low maintenance cost and high operational flexibility. Therefore, it is necessary to find out some practical and efficient methods to solve the technical problems and to use the existing systems in a better way. In response to the demands, this PhD work is performed aiming to explore the potentials of the existing railway catenary systems.

Table 1.1: System parameters of four Swedish catenary systems [6].

<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 kN</td>
<td>15 kN</td>
<td>9.8 kN</td>
<td>15 kN</td>
</tr>
<tr>
<td>Catenary wire tension</td>
<td>7.0 kN</td>
<td>15 kN</td>
<td>9.8 kN</td>
<td>15 kN</td>
</tr>
<tr>
<td>Span length</td>
<td>60 m</td>
<td>60 m</td>
<td>60 m</td>
<td>60 m</td>
</tr>
<tr>
<td>Stitch wire</td>
<td>Yes</td>
<td>Yes</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>Pre-sag in mid-span</td>
<td>30</td>
<td>0</td>
<td>30</td>
<td>30</td>
</tr>
<tr>
<td>Operational Speed</td>
<td>200 km/h</td>
<td>250 km/h</td>
<td>180 km/h</td>
<td>220 km/h</td>
</tr>
</tbody>
</table>

The PhD thesis work is performed based on numerical studies, focusing on identifying the dynamic features of the pantograph-catenary systems in different working conditions and establishing possible methods for dynamic improvement based on the existing pantograph-catenary systems. In order to take advantage of the merits of the existing systems and to overcome the possible technical difficulties, some solutions are proposed and discussed. In Chapter 2, an overview of the pantograph-catenary dynamics is given and some research topics are shown. In Chapter 3, some fundamental knowledge of numerical modeling is given and a 3D finite element (FE) model used in this thesis is introduced. In Chapter 4, a summary of the appended papers is given. Finally, in Chapter 5, some conclusions from this PhD work are drawn and the future work is proposed.
2 Pantograph-catenary dynamics

The pantograph-catenary interaction is one of the key issues in railway dynamics. Because the two contact surfaces have to withstand heavy electric load, high sliding speed and unpredictable environmental disturbances, a stable contact between pantograph and catenary is not easy to sustain in reality, especially at high speeds or in multi-pantograph operation. The contact quality between two surfaces is mainly determined by the contact force, that is, the higher the contact force the tighter the contact between the two surfaces. However, the contact force must be optimized, otherwise there would be some problems emerging, as shown in Figure 2.1. Too high contact force would lead to excessive mechanical wear and thus shorten the service life of the entire system. Too low contact force is also a concern which can cause poor quality of current transmission and electrical discharge, which contributes to electrical erosion and electromagnetic interferences with the telecommunication and signaling system in the neighborhood [1]. In some extreme cases, the pantograph suffers from serious damage and even tears down the catenary. As the dynamic behaviour is very important to the operability of railway operation, it has given rise to the interests of engineers and researcher. This section gives a brief introduction about the pantograph-catenary dynamics, and then describes some ongoing research orientations.

Figure 2.1: Technical concerns of pantograph-catenary system: (a) Wear on pantograph [48]; (b) Wear on contact wire [49]; (c) Arcing between pantograph and catenary [50]; (d) Structure damage of the pantograph-catenary system [51].
2.1 Fundamentals

The decisive criterion for the evaluation of the contact quality is the contact force between the contact strips of pantograph and the contact wire of catenary. Since there are some structural errors, micro irregularities on the contact wire, and environmental disturbances, the contact force must be high enough to tolerate these uncertainties. In order to effectively extend the service life of the pantograph-catenary system and reduce the maintenance cost, the contact force can be set neither too high nor too low. Therefore, it is necessary to keep the contact force within a certain range and suppress the fluctuation of the contact force during operation. As the contact force is subjected to a lot of influencing factors, in reality it is impossible to judge the dynamic performance simply by the contact force only in time domain. Therefore, according to EN 50317, statistical analysis of the contact force is usually used for both on-track measurement and simulation. The key parameters to evaluate the dynamic behavior of the pantograph-catenary system are [52]:

- 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.

Although the statistical results do not reflect any real properties in the contact, they makes it possible to correlate the dynamics in different working conditions and with different systems. There are different limits to the statistical maximum and minimum with respect to the contact forces for different systems. The mean contact force is mainly determined by the uplift force exerted by the pantograph.

For the mean contact force, there are target values of the mean contact force in Sweden, \( M = 0.00097v^2 + F_{\text{static}} \), which contains aerodynamic component related to the operational speed \( 0.00097v^2 \), and the static component \( F_{\text{static}} \). At any speed, the standard deviation should always be less than 30\% of the mean contact force [53].

There are also some other requirements to be fulfilled. Uplift is not a problem in most cases, because the entire catenary can move up and down together. However, if very high uplifts in the catenary system occur at the steady arms, it can make the steady arms hit the other stationary structures when the pantograph is passing. Therefore, to ensure operational safety, the permissible maximum uplift at the support is restricted to \( 50+0.00175v^2 \) according to EN 50317.
Although the contact force is used to describe the contact between pantograph and catenary, it is very difficult to directly measure the force between the two sliding surfaces. Therefore, in most cases, the contact force is measured through an indirect method, which involves two measuring steps, that is, the supporting forces at the frame and the inertia force of the contact strip, as shown in Figure 2.2. The supporting forces at the frame are measured by force transducers mounted between contact strip and pan-head, and the inertia force of the contact force is measured by accelerometers. The contact force on each contact strip is therefore derived as

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

(2.1)

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 [54].

![Figure 2.2: Measurement of the contact force between pantograph and catenary [54].](image)

**2.2 High-speed catenary**

The catenary system is suspended at poles or other similar supporting structures. As the support of the catenary is not continuous, it forms spans and thus there is always stiffness variation within a span, as shown in Figure 1.7. From the construction aspect, the span length between the supports is desired to be built as large as possible, but too large span length leads to large stiffness variation in reality. Normally, most of the catenary systems have their span lengths built around 50 m and 60 m. The vertical stiffness is always low in mid-span and high around supporting point. At low speeds the vertical stiffness variation is not a big concern, but with speed increasing, it enlarges the vertical movement of the pantograph and seriously exaggerates the dynamic interaction. It is quite important to reduce the stiffness variation, so there are many catenary designs which can narrow the stiffness variation, as shown in Figure 2.3. The catenary used for trolley service cannot even keep its own geometry level due to gravity, while railway catenaries easily sustain the contact wire level or as needed by conducting its gravity to the messenger wire above it and adjusting the length of each dropper. From the vertical stiffness aspect, the
additional stitch wire in the stitched wire catenary balances the stiffness discrepancy between mid-span and supporting pole, and the additional auxiliary wire in the compound catenary makes the contact wire better suspended than the simple catenary system. However, complexity needs money, so the stitched wire catenary system is more popular around the world than the compound catenary.

Besides the designs with low stiffness variation, the most widely-used method to achieve a good performance at high speeds is to increase the tensile forces applied to the wires of the catenary system. Higher tensile load can not only make the wires stiffer, as shown in Figure 1.7, but also increase the wave propagating speed on the wires, which will be discussed in Chapter 3. At present, all catenaries for high speeds use highly-tensile designs, as listed in Table 2.1. In the high-speed catenary Re 330 in Germany, capable of 350 km/h, the tensile forces on the contact wire and the messenger wire are 27 kN and 21 kN, respectively. In the record-setting test in 2007, SNCF achieved a speed of 574 km/h with help of highly-tensioned catenary system of 40 kN. In order to withstand very high tensile load, the high-speed catenaries are usually made of copper alloy. Compared with the catenary systems used elsewhere, the Swedish catenary systems are relatively soft and have large stiffness variation, especially for the widely used systems, SYT 7.0/9.8 and ST 9.8/9.8. Although high tensile forces on the catenary are quite efficient to improve the dynamic performance at high speeds, due to the material strength of the catenary, the tensile load cannot go to infinity in the future.

![Comparison of four types of catenary systems](image)

Figure 2.3: Comparison of four types of catenary systems: Trolley catenary, simple catenary, stitched catenary and compound catenary (from upper to lower) [2].
As the stiffness variation is periodically repeated in every span, high around supporters and low in mid-spans, there is another mean to compensate the stiffness variation, that is, a slight pre-sag of the contact wire in the mid-span, as shown in Figure 2.4. The pre-sag is introduced to reduce the vertical movement of the pantograph due to the low stiffness in mid-span. If the contact wire is levelled without any sag in the mid-span, the pantograph lifts the contact wire more in the mid-spans than around the steady arms. The pre-sag compensates the over-lifted height and makes the height of the pantograph relatively constant, so the dynamic oscillation of the pan-head can to some extent be suppressed. However, the pre-sag should be well designed with respect to the type of catenary and the targeted operational speed. Although the pre-sag can be easily adjusted by the length of droppers, an improperly-set pre-sag may act as irregularity on the contact wire and deteriorate the working performance. For high-speed catenary systems, the pre-sag is rarely used, because the stiffness variation within a span is very small and very little pre-sag is needed in reality.

Table 2.1: Tensile force applied to high-speed catenary systems [55]

<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.

Figure 2.4: Pre-sag in the mid-span of a simple catenary system [2].
Beside the fundamentals mentioned above, there are also some other measures to pursue a better dynamic performance. Dropper slackening is one of the main reasons for the non-linearity of the pantograph-catenary system. When a pantograph is passing the position with a dropper above, the pantograph lifts the contact wire a distance. Because the dropper can only bear tensile load and the dropper is thus slackened, the uplift of the contact wire shortly makes the disconnection between the contact wire and the messenger wire, as shown in Figure 2.5. Actually, this is a beneficial effect, because it can make the contact wire well suspended to the messenger wire, without causing any hard point on the contact wire. Regarding catenary overlap sections, the high-speed catenary systems usually use long overlap section, which can not only reduce the wave reflection caused by the fixed ends of the catenary but also make the transition within the overlap section as smooth as possible. In addition, due to the low damping of all kinds of catenary systems, different oscillations add together making a heavily excited background for the passing pantograph. The low damping significantly affects the dynamic performance, especially in multi-pantograph operation. Therefore, some additional damping is beneficial to stabilize the oscillation of the pantograph. In order to increase damping, some designs use rubber damping droppers or friction damping droppers, as shown in Figure 2.6. The applications can effectively reduce the amplitude of the high-frequency oscillations on the contact wire.

Figure 2.5: Dropper slackening when a pantograph passes [56].

Figure 2.6: Applications of rubber damping dropper in the catenary system [57].
In order to improve the dynamic performance or increase the operational speed of an existing catenary system, some technical upgrading is always needed. However, any form of upgrading needs not only investment but also a long suspension of service. For existing lines connecting the major cities all around the world, it is almost impossible to entirely upgrade the existing catenary network in this way. It is therefore necessary to find some effective and efficient methods to achieve this goal.

2.3 Multi-pantograph operation

Multi-pantograph operation, which is widely used in many countries, is a special operational condition, in which there are two or even more pantographs in contact with catenary. Normally, there is only one pantograph in use for each locomotive or EMU unit, but in some special services, e.g. if additional power is required and higher capacity and flexibility is needed to meet passenger-flow variation, two or even more short trainsets are coupled together and several pantographs are in contact with the catenary at the same time, as shown in Figure 2.7. The multi-pantograph operation can provide not only sufficient energy to power the train but also redundancy in case of system failure. Even though multi-pantograph operation is an efficient method to use rolling stock and infrastructure, it gives some drawbacks during operation. At low speeds, regardless the electric concerns, there is almost no difference between single-pantograph operation and multi-pantograph operation. However, with speed increasing, the dynamic interaction between pantograph and catenary gets intensified and the pantographs heavily interfere with each other, because they are coupled through the catenary. The system becomes more complex and more sensitive than the single-pantograph system.

![Figure 2.7: The Swedish Regina train with two pantographs in operation [58].](image)

In most cases, the trailing pantograph gives bad performance, as shown in Figure 2.8. The leading pantograph heavily excites the catenary, while the trailing pantograph has to confront not only the wave exited by itself but also a much more complex working
background of the catenary. Since the catenary is a low-damped structure, the influence between pantographs is strong at short spacing distances. If the dynamic load of the trailing pantograph is not suppressed, the trailing pantograph can cause more wear on the catenary and reduce the energy that it can provide to the train. In practice, to sustain a good quality of current collection and avoid risking operational safety, today there are strict regulations, which limit the minimum spacing distance between pantographs and the number of pantographs with respect to the type of catenary system. In some extreme cases in Sweden, even though the spacing distance is set to be 160 m, there is still too much contact loss between pantograph and catenary, and it can sometimes trigger the electric protection to switch off the affected train automatically. To avoid disturbing the timetable of the entire railway network, some configurations of the coupling trainsets are not allowed to be used and some trainsets with multi-pantograph operation have to significantly lower their operational speed than the permissible speed of the railway line. Multi-pantograph operation which sometimes restricts the operability of the railway systems is not a good and efficient way to use the transport capacity and even causes some technical problems, so today it has drawn great attention from both industry and academia.

As we can see from Figure 2.8, the spacing distance between pantographs is very important for the trailing pantograph, because at the same operational speed the contact forces with respect to two spacing distances differ very much, even frequently dropping to zero with an improper spacing distance as seen in Figure 2.8 (a). In reality, the spacing distance must be carefully investigated to avoid risking the operational safety. Besides the spacing distance, the performance of multi-pantograph operation is also highly related to the type of the catenary and the operational speed, as shown in Figure 2.9. This figure compares the standard deviations of two Swedish catenary systems in multi-pantograph operation as a function of speed. For both catenary systems, the standard deviations increase with speed. For catenaries with high tensile forces, the standard deviations can significantly be reduced in the same working conditions compared with the soft catenary system and it is generally more suitable for multi-pantograph operation. In addition, we can find that the soft catenary is quite sensitive to the number of pantographs in use and the spacing distance between pantographs. However, in one case, e.g. the pantographs are well spaced at 120 m, the soft catenary can almost work as well as the stiff catenary. Therefore, we can conclude that the multi-pantograph operation in soft catenary systems is very complicated and needs very careful investigation.
In order to improve the dynamic performance and to increase the service speed, the most common method to increase the service speed is to replace the existing system with a stiffer system, which has less stiffness variation and higher critical speed. There is another way to improve the dynamic performance by optimizing the pantograph. The pantographs can be classified into three main types, that is, Z-shape pantograph, diamond-shape pantograph, and T-shape pantograph, as shown in Figure 2.10. Today, the most widely used catenary is the Z-shape pantograph, while the T-shape design is mainly used with respect to aerodynamic and noise concerns. Since the pantograph is a protruding structure out of car body, it contributes a lot to the aerodynamic drag and noise emission, especially at high operational speeds. By now there are many aerodynamically-friendly pantographs.
developed. To minimize the inertia load caused by the pantograph, the weight of the contact strips is kept as low as possible and the pan-head is well suspended. In addition, the pantograph structure is designed to withstand environmental disturbances, e.g. wind turbulence, irregularity on contact wear and vibration from car body.

Figure 2.9: Standard deviation of contact force as a function of speed with five spacing distances between pantographs: (a) single-pantograph operation; (b) the second pantograph in two-pantograph operation and (c) the third pantograph in three-pantograph operation.
Figure 2.10: Three types of pantographs: (a) Z-shape pantograph; (b) diamond-shape pantograph; (c) T-shape pantograph [59].

With the development of control strategies and actuators, actively-controlled pantographs are proposed, in which the pantograph can adjust itself to closely follow the stiffness variation and movement of the catenary. The fundamental idea of the active control pantograph is to detect or estimate the discrepancy between the real contact force and the desirable value, and let the servo-actuator correspondingly react to compensate the discrepancy. One of the active control models is shown in Figure 2.11. There are also many other active systems and control strategies which have been studied and tested, e.g. by measuring the velocity or estimating the stiffness variation in the corresponding working conditions. The aim of all the strategies is to keep the contact force as constant as possible. To meet the safety requirement during operation, the current transmission has to be ensured by the passive structure of the catenary even if the actively-controlled system fails. In addition, the application of the actively-controlled pantograph needs a large-scale modification on the existing pantographs.

Figure 2.11: Simulink model of an actively-controlled pantograph with PID control [44].
3 Numerical modelling

The dynamic interaction between pantograph and catenary is an important issue concerning design, construction, maintenance, safety and operability. It is always necessary to perform careful investigation once there are some technical changes to the pantograph-catenary systems to ensure safety, reliability and feasibility. However, on-track tests are not only costly and time-consuming but sometimes even risky. In addition, since the pantograph-catenary system is a complex structure and subjected to a great number of influencing factors, not all details of the system are observable or detectable. With the development of computer technology, it has become more and more popular to study the pantograph-catenary system through numerical methods. Numerical studies allow manageable and observable conditions to perform very detailed investigation, which is sometimes very hard or even impossible to do in a real test. Although numerical studies of the pantograph-catenary system are effective and efficient, it always requires properly identifying the system parameters and modeling in accordance with the real pantograph-catenary system. This section briefly introduces the modelling procedure of the pantograph-catenary system and the numerical model used in this thesis work.

3.1 Fundamentals

The pantograph-catenary system is a complex and nonlinear system and its dynamics is mainly determined by the system design as well as other environmental factors, such as wind load, gradient, curvature and structural errors. It is very critical to correctly express the dynamics of the pantograph-catenary system. Here the pantograph-catenary system is simplified to basically show its working mechanism.

The pantograph-catenary system can be regarded as the combination of some pre-tensioned strings and lumped masses with a moving load sliding against it, as shown in Figure 3.1. The system can be numerically described. Instead of string element, the catenary can be modeled with beam elements with bending stiffness, but the fundamentals are quite similar as shown below.

Figure 3.1: The simplified model of the pantograph-catenary system with pre-tensioned wires, lumped masses and moving load.
Since the vertical stiffness of the catenary is not uniform, as shown in Chapter 1, the periodical displacement in vertical direction caused by the uplift force excites the catenary and the waves spread forwards and backwards along the pre-tensioned wires. The speed of the wave propagation on the pre-tensioned structure, \( c \), can be approximated as

\[
c = \sqrt{\frac{\sigma}{\gamma}} = \sqrt{\frac{T_{CW}}{m'_{CW}}}
\]

(3.1)

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 [1].

However, as both the exited wave and the load move along the catenary, the moving pantograph has to slide against the already excited catenary and confront the wave excited by itself. In extreme condition, once the train reaches the wave propagation speed, two displacements caused by the static uplift and the wave propagated to the current position where the pantograph is are superimposed and the resultant displacement theoretically become infinitely high as energy accumulates. In reality, the dynamic performance gets significantly decreased if the operational speed approaches the wave propagation speed. Therefore, the wave propagating speed of the catenary is the critical speed of the system, which limits the operational speed. For all cases in which the train runs below the critical speed, the vibrating source is a pantograph moving along the catenary, so the frequency of oscillation is changed due to Doppler Effect. The Doppler factor, \( \alpha \), which describes the Doppler Effect on the pantograph-catenary system, is defined as

\[
\alpha = \frac{(c - v)}{(c + v)}
\]

(3.2)

where \( c \) is the speed of propagating wave on the catenary and \( v \) is the running speed of the pantograph.

The contact wire is assumed to be a smooth and uniform pre-tensioned string, but there are many substructures and lumped masses fixed to it, e.g. clamps, steady arm, droppers and other fittings, which make the mass distribution on the wire uneven. The propagating wave can be blocked and reflected by the uneven masses on the wire. The reflection of the propagating wave makes the working condition more complicated and can increase or decrease the amplitude of the oscillation on the catenary. In reality, the pantograph-catenary system is built up with more detailed substructures and involves more factors in order to correctly express the working performance, but the fundamental principle of the pantograph-catenary dynamics is as described here.

### 3.2 Pantograph

There are many methods to model the pantograph. The multibody pantograph model builds up the pantograph model according to the geometry and material properties of the...
real pantograph, considering the elasticity and the vertical and angular movements of the pantograph. A typical multibody model is defined as a collection of rigid or flexible bodies that have relative motions constrained by kinematic joints and act upon external forces. For the real system, the main engineering question is the contact between pantograph and catenary, so most of the study cases do not fully model the details of the pantograph structure in the investigation on pantograph-catenary interaction \[61\]. In addition, any small changes to the pantograph require a large amount of re-calculation. Therefore the multibody pantograph model is not widely used in the research of the pantograph-catenary dynamics today. Since the contact quality between the pantograph and catenary is the key issue that researchers and engineers care about, a lumped mass model of the pantograph is widely used today, because in most cases it is good enough to well reflect the dynamic properties of the pantograph from testing the dynamic response of the real pantographs. A low-order pantograph model with only several lumped masses is often used, either two-dimensional or three-dimensional. In this thesis, a 3D pantograph model is built up to investigate the dynamic interaction of the pantograph-catenary system, as shown in Figure 3.2.

![Figure 3.2: Low-order model of pantograph.](image)

In the model, the pantograph is simplified to 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 defined by second-order differential equations. The lumped masses are used to express multiple eigen frequencies. 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 two stopper gaps \((d_1, d_2)\). The frame is mounted on the moving base through a
combination of friction slider and damper to express the mechanical properties of the frame. Two vertical translational degrees of freedom of the two frame parts, and one rotational degree of freedom of the pan-head are considered in the model. The uplift force of the pantograph is defined as \(0.00097 \cdot v^2 + F_s\), and taken as a combination of a constant component on the frame \(F_s\) and an aerodynamic component related to operational speed \(v\).

### 3.3 Catenary

The catenary model can be built up by many different methods. The modal analysis method is based on calculation of a number of eigen frequencies and eigen values of the catenary systems, where a lot of computing effort can be saved. The catenary is a complex and nonlinear system. However, the model analysis method can neither take many influencing factors and details of the structure into account nor truly reflect the dynamic behaviour of the catenary system. The following issues are not considered in the model: wave propagation and wave reflection. Today, 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 number of degrees of freedom to be considered. A FE model gives relatively accurate solutions and allows modifications to be easily implemented. Many factors, e.g. non-linearity, damping, pre-sag and stagger, can be included in the model. In this thesis, a 3D catenary model is built up to investigate the system, as shown in Figure 3.3.

![Figure 3.3: Finite element model of catenary.](image)

The geometry of the catenary system is generated in the program BARTRAD, which is developed for Trafikverket (The Swedish rail and road administration). In the FE model used in this thesis, there are three types of wires used: contact wire, messenger wire and dropper. As the catenary is a long and thin structure, the contact wire is built up with tensioned Euler-Bernoulli beam elements, while the messenger wire is build up with truss
elements. For each node on the contact wire and messenger wire, it has six and three degrees of freedom, respectively. The droppers are built up with uniaxial spar elements with a bilinear stiffness, which deform elastically under tensile force and insulate the axial compressive force. A continuous range of 20 spans is modelled. Lumped masses are introduced to describe the clamps, which connect both the contact wire and the catenary wire to the droppers. At each end of the 20 spans, tensioning forces in the longitudinal direction are applied on both the contact wire and the catenary wire. As it is a 3D finite element model, it also takes steady arm and zig-zag suspension into consideration. The steady arm connects the contact wire and a rotational joint at the supporting structure, as shown in Figure 3.4. The system is assembled with the FE method and the equations of motion can be written as

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

(3.3)

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, i.e. velocity and acceleration vectors, respectively. The catenary is a very low damped structure. Here proportional damping is introduced to form the damping matrix \( C \), which is given as a linear combination of the stiffness \( K \) and mass \( M \), known as Rayleigh parameters, and can be written as

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

(3.4)

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

Figure 3.4: Steady arm structure in 3D model.

3.4 Contact

The contact between pantograph and catenary is the key issue in the pantograph–catenary dynamics. Two systems are coupled at the contact point and thus dependent on each other. In most studies, the friction component of the contact force between the two surfaces is neglected. There are two main methods widely used to model the contact without friction component. One method treats the contact as a rigid constraint with local equilibrium equations, in which the kinematic condition of non-penetration between the pantograph and the contact wire is adopted. The other method is the penalty method to approximately
account for the constraints acting at the interface between pantograph and catenary, in which the contact force is based on a penalization of the interpenetration between the two surfaces. In this thesis, the penalty method is used to determine the contact force between pantograph and catenary.

In the model, two types of elements are used, that is, 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 3D line/line contact pair. The contact force emerges only when the contact element on the pan-head penetrates the target element on the catenary. The contact force $F_c$ is defined as

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

$$0, \quad \text{if } g > 0$$

(3.5)

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

The Newmark method is used to perform numerical time integration. Every time step, non-linear effects caused by dropper slackening are checked and the global stiffness matrix is updated.

3.5 Validation

It is very important to validate the numerical model to ensure that the model can correctly reflect the dynamics of the real pantograph-catenary system. According to EN 50318, the mean contact force from simulation must be within ±10% of the tolerance range of the mean contact force from on-track tests, while the standard deviation should be within the range of ±20%.

The validation of this model is performed on four catenary systems in Sweden at speeds up to 250 km/h. The difference 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.

Figure 3.5 shows the comparison between the simulation result and the measured result of the Swedish SYT 7.0/9.8 catenary system. We can see that there is a good agreement between the two results. In addition, the numerical model joined a benchmark exercise, which involved 10 simulation codes from universities and research centers across the world, and the comparison showed that the numerical model used in the thesis is in good agreement with other pantograph-catenary numerical models, which ensures the correctness and effectiveness of the following study.
Table 3.1: Validation according to EN50318 – difference at maximum in standard deviation

<table>
<thead>
<tr>
<th>System</th>
<th>Tension force (kN)</th>
<th>Stitch</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>
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<td>No</td>
<td>2</td>
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<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 3.5: Comparison between simulated (a) and measured (b) contact force for single pantograph operation on SYT 7.0/9.8 catenary system.
4 The present work

The railway pantograph-catenary system is one of the key issues, which determines the operational speed and maintenance cost of railway systems. The pantograph-catenary system has a complex structure and is directly subjected to environmental impacts. The newly built high-speed systems can easily cope with high speeds and provide good performance. But the existing catenary systems, which have been developed many decades ago, are too soft and sensitive to withstand environmental disturbance, and they give relatively bad performance and shorten the service life of the key components. However, any kind of upgrading is costly and time-consuming. Considering the large scale and heavy service duty of the existing railway network, it is almost impossible to completely upgrade the existing catenary systems, so it is necessary to find out practical and efficient solutions to increase their operability and stability.

The present PhD thesis work is performed through numerical method to identify the dynamic properties of the pantograph-catenary system in different working conditions, to enhance operational efficiency and stability of daily operation, and to explore potentials for better usage of the existing pantograph-catenary systems for the future. To improve the performance of the existing systems and avoid large-scale modification, some technical measures are proposed within this PhD study. This PhD work is summarized as follows and detailed in the appended papers.

4.1 Summary of Paper A

Paper A investigates the dynamic behaviour of multi-pantograph operation on Swedish soft catenary systems. This paper builds up a 3D pantograph-catenary model for the computational analysis of the interaction between catenary and pantograph, which considers the zig-zag suspension and steady arm of catenary and pan-head rotation, and is validated by comparing simulation results against on-track tests. Since in multi-pantograph operation the pantographs heavily affect each other and often gives bad performance for the interaction of the second pantograph with the catenary, the multi-pantograph operation has become a big concern in the pantograph-catenary system. This paper discusses the working conditions with up to three pantographs, with speeds ranging from 180 km/h to 280 km/h, and with spacing distances between 60 m and 120 m. The results show that a leading pantograph is little influenced by any pantograph behind it while a trailing pantograph is heavily affected by all the pantographs ahead of it. The spacing distance between pantographs is the most critical factor that affects the whole system in multi-pantograph operation. It is not necessary to always keep the spacing distance as large as possible to reduce the interaction between pantographs and a properly-
selected spacing distance can still maintain a good dynamic performance for the trailing pantographs. This paper shows that it is possible to operate the coupled trainsets with up to three pantographs in use and still sustain good current collection, as shown in Figure 4.1.

Figure 4.1: Comparison of the standard deviations of three-pantograph operation with spacing distance at 120 m. Working condition: WBL88 pantograph, SYT 7.0/9.8 catenary.

4.2 Summary of Paper B

Paper B investigates the two-pantograph operation at short spacing distances, where the influence between the pantographs becomes significant and noticeable. Based on the conclusions in Paper A, it is not necessary to avoid multi-pantograph operation or to set the spacing distance very big to reduce the influence between pantographs. This paper further investigates how the two pantographs affect each other in two-pantograph operation with pantographs spaced from 30 m to 60 m. This paper shows that although the trailing pantograph does not work as well as the leading pantograph in general, at some certain spacing distances some significant improvement happens to the trailing pantograph, so that it performs even better than in single-pantograph operation at a much lower speed, as shown in Figure 4.2. Today there are always two pantographs mounted on each trainset, but only one of them is raised up and in use during operation. The results in the paper indicate that if the spacing distance between the pantographs can be well placed, the existing pantograph-catenary system can be qualified for a higher speed. To overcome the difficulty caused by the leading pantograph and to achieve speed increase in the entire system, this paper proposes auxiliary-pantograph operation to effectively use the pantograph-catenary system, in which the leading pantograph is not responsible for power transmission but for creating a favourable working condition for the trailing pantograph.
Figure 4.2: Standard deviations of the contact force of the trailing pantograph as functions of both running speed and spacing distance. Working condition: Pantograph: WBL88, Catenary: SYT 7.0/9.8, two-pantograph operation. The meshed area marks the cases where the leading or trailing pantograph works even better than in single-pantograph operation at 200 km/h, the maximum design speed.

4.3 Summary of Paper C

Paper C addresses the influencing mechanisms of the phenomena occurring in two-pantograph operation at short spacing distances and further investigates the possibility to implement the auxiliary-pantograph operation as proposed in Paper B. This paper shows that with a properly-designed spacing distance in two-pantograph operation, the catenary can be excited on purpose by the leading pantograph and therefore the contact force of the trailing pantograph can be adjusted. In addition, the two identical waves caused by the two pantographs propagate at the same speed and severely interfere with each other, which is helpful to create a favourable working condition for the trailing pantograph. This paper shows that further improvement can be achieved if a reduction of the uplift force is applied to the leading pantograph, as shown in Figure 4.3, which is beneficial for both speed increase and wear reduction in the implementation of the auxiliary-pantograph operation. The paper shows that the auxiliary-pantograph system has some tolerances to small deviations of some key parameters and still works well within a wide range of system damping applied. Based on the investigation, this paper shows that it is a feasible and practical way to increase the operational speed without large-scale modification taking place, and gives some proposals on the implementation of auxiliary-pantograph systems.
Figure 4.3: Comparison of standard deviations between auxiliary-pantograph operation with uplift force reduction on the leading pantograph at 260 km/h and single pantograph operation at 200 km/h in the same condition.

### 4.4 Summary of Paper D

Paper D discusses the influence of pantograph raising and lowering in multi-pantograph operation. When a train passes through special sections or in an emergency condition, it is necessary to lower one or all of the pantographs and then raise them up again. Since the multi-pantograph system is more sensitive and vulnerable than the single-pantograph system, any motion in any of the pantographs can not only introduce a sudden impulse to the catenary but also significantly change the configuration of the system. To keep dynamic stability and to avoid disruption, this paper studies the dynamic behaviour of the multi-pantograph operation during pantograph raising and lowering under the conditions: up to three pantographs, various pantograph raising/lowering orders and different operating positions in a span. This paper shows that the leading pantograph is little influenced by the raising and lowering movement of any pantograph behind it, but any trailing pantograph is significantly affected by any operation taking place ahead of it. The dynamic performance of the system depends on the pantograph spacing distance and the operational speed, but is little affected by the operating position in a span. In addition, this paper also discusses the auxiliary-pantograph operation in pantograph raising and lowering operation, and suggests specifying the speed where the auxiliary pantograph gets into or out of service to avoid disruption.

### 4.5 Summary of Paper E

Paper E studies the dynamic behaviour of the pantograph-catenary system in a catenary overlap section. The catenary system is desired to be built smooth and uniform in geometry and elasticity along the running direction, but in reality, the entire catenary must be divided into many tensioning sections due to electric concerns and tensile force
retention. Therefore, an overlap of several spans between the neighboring tensile sections is implemented to provide a smooth transition for the passing pantograph, as shown in Figure 4.4. However, when upgrading the existing catenary system for a higher speed or in multi-pantograph operation, its dynamic behaviour in the overlap section is not as good as in the middle spans of each tensioning section. This paper investigates the impact of the following issues on the dynamic behaviour in this special section: operational speed, wire gradient, damping ratio, and spacing distance in multi-pantograph operation. This paper indicates that the gradient of wires in overlap sections and the damping ratio have great influence on the dynamic performance, especially at high speed and in multi-pantograph operation. A high damping ratio is beneficial to sustain the good dynamic performance in the catenary overlap section.

Figure 4.4: Sketch of catenary overlap section.

4.6 Summary of Paper F

Paper F presents the influence of lumped-masses of the catenary system on the dynamic performance. There are many kinds of lumped-masses in use in the catenary systems, such as droppers, clamps and other fittings, but practically they are now supposed to give negative impact and normally kept as light and small as possible to minimize disturbances. In reality, these masses cannot be completely removed but can easily be adjusted during maintenance. Through the investigation on the lumped-mass of the catenary system, this paper shows that the lumped-mass on the catenary does not always give negative impact and can improve the dynamic performance if the mass can be applied at some favourable locations, as shown in Figure 4.5. The influence of the lumped-mass only takes place within a small range and becomes stronger in multi-pantograph operation and in the auxiliary-pantograph system. To avoid hard-point effects caused by the additional lumped-mass, this paper suggests that the artificial mass can be installed on the messenger wire of the catenary rather than on the contact wire. Based on the discussion, this paper proposes a method to improve the dynamic performance or correct structural defect at the places as needed by re-arranging the existing lumped-masses on the catenary.
Figure 4.5: Comparison of contact forces as a function of location between single-pantograph operation and lumped-mass applied at stich wire. Working condition: speed: 200 km/h, lumped mass: 1 kg, system: SYT7.0/9.8 catenary.

4.7 Summary of Paper G

Paper G addresses the working mechanism of the artificial mass and investigates the possibility to turn the mass into a tuned-mass system to achieve further improvement. It is always important and desirable to find out simple and practical methods to improve the dynamic behaviour of a specific structure. Due to vertical stiffness variation and wave propagation along the catenary, the fluctuation of the contact force becomes significant with operational speed, and wire misalignment, structural errors and uneven mass distribution of the catenary can further deteriorate the contact stability. In reality, we can do nothing to easily upgrade the existing catenary system but reconstruction. However, in other engineering applications, some well-designed mass systems are employed to benefit their dynamic performances. Inspired by them, this paper investigates the possibility to similarly apply a tuned-mass system to modify the dynamic performance as needed. As shown in Figure 4.6, the dynamic performances are changed with different stiffness of the mass connection. This paper shows how the tuned-mass system works in the pantograph-catenary system and gives some suggestions on implementing the tuned-mass system on the existing catenary system. Through the discussion, this paper gives an option to improve the dynamic behaviour of the existing system and to easily overcome some technical difficulties in reality.
Figure 4.6: Comparison of the contact forces as a function of location with (...) and without (--) the mass tuned. Working condition: catenary: SYT 7.0/9.8, speed: 200 km/h, lumped-mass: 1 kg placed between the 4th and 5th dropper on the messenger wire, tuning stiffness: 1000 N/m.
5 Conclusions and future work

5.1 Conclusions

The purpose of this PhD study on pantograph-catenary dynamics is to investigate the dynamic behaviour of the existing Swedish pantograph-catenary systems, to identify the main influencing factors, to propose some practical solutions to the current technical problems, and to explore the potential of the existing systems for a better utilization in the future, which would be beneficial to the infrastructure owners, the rolling stock manufactures and operators. In order to enhance the operability and stability of the existing pantograph-catenary systems, the following studies are carried out in this work: the dynamics of single and multiple pantograph systems, the operation in special sections, the operation in abnormal working conditions, the influence of lumped-masses on the catenary, the application of an auxiliary pantograph and the application of a tuned-mass system. All studies within this thesis are performed through numerical method with a 3D finite element (FE) pantograph-catenary model.

With the rapid development of railway technology and fast expansion of railway networks, nowadays it is possible to operate trains at a speed of 350 km/h or even higher on newly built high-speed lines. However, since railway pantograph-catenary systems have been developed and built for decades, the normal-speed catenary systems still take a large proportion around the world. Compared with the high-speed designs, they are relatively soft, which seriously limits the operational speed, increases the wear rate of key components, and lowers the reliability of operation. While technical upgrading on these systems requires both large investment and long out-of-service time, it is almost impossible to completely upgrade all the existing pantograph-catenary systems. To meet the huge demand for higher speed and more stable operation of the existing pantograph-catenary systems, this work is therefore conducted.

The thesis concludes that although in multi-pantograph operation the pantographs significantly affect each other and often give rise to bad performance of the trailing pantograph, it is not necessary to avoid multi-pantograph operation or set the spacing distance between pantographs as large as possible. The reason is that the dynamic behaviour is determined by the combination of operational speed and spacing distance. For a specified working condition, the spacing distance between pantographs is the most critical factor and some technical difficulties in multi-pantograph operation can be solved by correspondingly optimizing the spacing distance between pantographs.

The thesis proposes an operational condition based on the existing systems for better working performance or higher operational speed, where the leading pantograph is no longer responsible for power transmission but creates a favourable working condition for the trailing pantograph. Since there are always two pantographs mounted on each trainset,
it would be a possible and practical solution to enhance the operability of the existing pantograph-catenary systems if the spacing distance between pantographs and the uplift force of the leading pantograph is well-designed.

The thesis investigates the dynamic behaviour of the pantograph-catenary system in pantograph raising and lowering condition and in catenary overlap section to ensure operational safety. Because the trailing pantograph has a large impact on the trailing pantograph, any motion of the leading pantograph should be very careful when the train operates at the full permissible speed of the line. Regarding catenary overlap section, the wire gradient of the catenary should be well-designed and high damping is beneficial to keep a smooth transition of the pantograph.

This thesis proposes a method to improve the dynamic performance or to adjust the dynamic performance at the needed locations, by applying some artificial tuned-mass systems to the existing catenary systems. The amount of weight, the location and the elasticity of the connection must all be well tuned as needed to optimize the dynamic performance of the existing system. Since there are many types of clamps and other fittings built for structure support or electricity circuiting, it can also be an efficient and effective solution to install some tuned-mass systems on the existing catenary systems for dynamic purpose.

5.2 Future work

This thesis shows the dynamic behaviours of the soft pantograph-catenary systems and gives some possible solutions to practically increase the working capability of the existing pantograph-catenary system. However, in general, this thesis performs all the studies with numerical methods and in idealistic working conditions. As the pantograph-catenary systems have a rather complex structure and are subjected to a great number of influencing factors, it is almost impossible for the numerical model to fully reflect the real working conditions of the pantograph-catenary systems. This thesis only theoretically analyses their dynamic properties and provides some possible options for the development. In the future, more influencing factors, such as curves, disturbances and structural errors, will be studied and included in the numerical model. Last but not least, all the inputs in simulation can only be derived from measurements on the real pantograph-catenary systems and all suggested solutions can only be validated through on-track test. Therefore, in the future more measurements and tests about the real pantograph-catenary systems are going to be performed on the way to enhance the dynamic performance of the existing pantograph-catenary systems.
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