Dynamic implications for higher speed in sharp curves of an existing Norwegian overhead contact line system for electric railways

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ABSTRACT: A two level overhead contact line system and a train pantograph are used to supply the power to the electric railway vehicles in Norway. For this power supply to be reliable and uninterrupted, also for higher speed rail, there must be strict static and dynamic requirements for the contact line characteristics. Due to the Norwegian topography the national railway network is particularly characterized by numerous and sharp curves, often with a radius well below 1000 m. The dynamic behaviour in the overhead contact line section which includes sharp curves is expected to be different from similar, but straight sections. This study looks primary at dynamic implications in evaluation of the catenary system. Usually, it is assumed that for high speed railway overhead contact lines no significant dynamic response is present below 200 km/h due to the system design. However, these effects will for some existing systems designed for lower speed appear at much lower speeds. An existing partly curved section is investigated for train speeds of 90, 130 and 160 km/h. The section chosen has a curve with a radius as low as 350 m. This is compared with a 1250 m radius curve on the same section and with a straight segment section. The pantograph-contact line interaction is simulated by a 3D finite element model including the Norwegian catenary system Tabell 54 and a commonly used pantograph, WBL 88. The present investigation shows how optimizations for some segments of the section at hand will introduce non-optimal response in others. This may lead to an increased wear of the contact line and increased motion of the pantograph and possible loss of contact.

KEY WORDS: Catenary system; FE-modelling; System identification; Transient dynamic response; Catenary-pantograph interaction; Contact wire; Numerical simulations.

1 INTRODUCTION

A challenging topology is a common feature for most relevant routes where high speed rail may be considered introduced in Norway. This may introduce high costs to actualize the goal of high speed rail, i.e. train velocities above 250 km/h. Nevertheless, there is an ever growing interest to explore an increase in speed on the already existing railway infrastructure. It is then very important to investigate possible limiting factors. This paper will focus on the dynamic behaviour of an existing Norwegian overhead contact line system, named Tabell 54, in sharp curves. The train power collector interacting with the contact line system is a commonly used pantograph, WBL 88 by Schunk Nordiska AB, used on the Signatur train (NSB Class 73, NSB - Norwegian State Railways). This paper explores the dynamic implications by sampling displacements from different points on a numeric model of the overhead contact wire system. All structural systems that may experience excessive vibrations due to changes in loading should be evaluated for their dynamic properties and corresponding response under new operational situations. For the electric railways and its current supply system it is necessary to include two separate dynamic systems; the train pantograph system and catenary contact wire system. Both systems have their own specific characteristic dynamic properties that must work well separately as well as together. Since this interactive system includes one dynamic system in motion and one stationary in space, data sampling or monitoring must be done separately. Of course it would be ideal and also possible to have an integrated system which simultaneously samples from the two. However, this is seldom practical due to the complexity of the control system and the diversity of operators within the railway industry.

There are several publications that focus on the development of optimized pantograph, where analyses are performed on the pantograph’s design variables. These may cover the head mass, head stiffness etc. [1, 2, 3]. Other publications focus on the sampling of several different parameters measurable on a pantograph. For instance the contact forces on the carbon strips of the pan head may be evaluated at several connector points. Non-linear properties such as connector friction, aerodynamic forces, non-linear damping and stiffness, or the static and dynamic uplift force are others [4, 5, 6]. At the same time it seems that there are a lot less work published on the measurements made exclusively on the catenary system, see [7, 8, 9].

Usually, it is assumed that for high speed railway overhead contact lines no significant dynamic response is present below 200 km/h due to the system design. However, for some existing systems designed for lower speed these effects will appear at much lower speeds. Systems with several and sharp curves that originally were designed for train speeds around 90 km/h is today operated at speeds already exceeding this, and the demand for higher speed is increasing. Dynamic simulations of such systems show significant dynamic response already at levels around 130 km/h. Forces in the overhead contact system in such tight curves will be different from those expected on similar, but straight segments. It is
partly due to this that only 35% of the existing railway lines can handle velocities above 100 km/h [10].

2 RAILWAY CATEenary SYSTEMS

The railway catenary system consists of a contact wire, a messenger wire, droppers, registration arms and brackets as can be seen in Figure 1 and Figure 2. The contact wire is the conductive part which transfers the electricity to the train through the pantograph. The messenger wire carries the contact wire via the droppers, and makes it possible to obtain the desired geometry, stiffness and elasticity. The brackets carry the messenger wire and are fastened to the poles along the line. The main function of the registration arms, which are fastened to the contact wire at the supports, is to obtain the right horizontal geometry of the contact wire.

![Figure 1. A discretization of the catenary system between poles. SH is the system height, and L is the length of one span, her 60m.](image1)

To transfer the electrical power from the contact wire to the train there is mounted a device called a pantograph on top of the train. Two bow strips of coal at the top of the pantograph are the actual components which transfers the electricity. This transfer is crucial for the running of the train thus there has to be uninterrupted contact between the pantograph and the contact wire. Simeon and Arnold [11] describes this contact as the most critical part in the transmission of the electricity to the trains of today. The contact is mainly ensured by introducing an upwards pressure in the pantograph.

To obtain the desirable geometry of the catenary system there is introduced tension in both the contact wire and the messenger wire. The wanted tension is obtained by the use of a tensioning device like the one shown in Figure 3. For further details of contact lines system for the electric railways see also [12]

![Figure 3. The tensioning equipment in use at the existing section.](image3)

![Figure 4. Zig-zag configuration along the track axis.](image4)

The vertical stiffness of the catenary system is an important property and is varying between the poles. The system is stiffer close to the pole support and softer at the mid-span. This is a railroad technology property often referred to as the elasticity and defined as the uplift of the contact wire per applied force as indicated in Figure 6. The estimated elasticity over a 40m long pole section, i.e. in a sharp curve along the Soknedal section is also shown in Figure 5. Typically, the elasticity is slightly lower at the vertical droppers.

![Figure 5. The elasticity along a pole span of 40m at Soknedal.](image5)
pantograph lift the contact wire more at the mid-point than at the pole. It is preferable to reduce this motion as much as possible. This can be achieved by introducing a pre-sag of the pole span. Thus, demanding a higher uplift at the mid-point to hold a constant absolute position of the pantograph head.

Figure 6. The uplift force by a pantograph on the contact wire, which also is the basis for the elasticity consideration.

The uplift is usually in design controlled at the pole support since that is most critical considering the possibility of arcing, i.e. pantograph may hook the cantilever pole support. However, the uplift motion at mid-span is equally important when considering the dynamic effects of the contact wire. Any excessive vibrations may cause several unfortunate responses such as: large initial vibrations at the upcoming pole which may lead to larger uplift, large initial vibration for trailing pantographs if the train set have more than one, generally large vibrations rendering loss of contact and thus loss of power and also increased wear of contact wire.

2.1 Norwegian railway catenary systems

The main existing catenary systems used in Norway are Tabell 54, System 35, System 20 and System 25. However, only the three latter can be chosen for new design [13]. The choice of system for the contact wire of new railway sections is thoroughly specified in the technical regulations. The criteria that decide which system to be used are: desired train velocity, type of pantographs allowed, density of trains, and also the type of tracks used [14].

The first system, Tabell 54, is an old catenary system widely in use on the existing railway sections. The maximum train speed allowed is at the present time 130km/h for this system, but it was originally designed for only 90 km/h. The original tension forces were then 7.6 kN in both the contact wire and the messenger wire, but to cope with the desired higher speed they were changed to 10 kN and 5 kN, respectively.

The main difference between system 35, 20 and 25 is that they are designed for different train speeds. System 25 is the Norwegian system designed for the highest train speed, a speed of 250 km/h and the minimum radii of the curvatures are 800 meters. The tension forces used in this system are 15 kN in both the contact wire and the messenger wire. The next system is System 20 which allows a maximum speed of 200 km/h, and has 10 kN in both wires. Finally, System 35 which has 7.1 kN tension in both wires, and allows a maximum speed of 130 km/h [15].

System 20 is split into four different groups; A, B, C1 and C2, where the two latter are tunnel catenary systems. System 20 A is developed for one pantograph with speeds up to 200 km/h where the radii of the curves should be larger than 800 meters. System 20 B is designed for train speeds only up to 160 km/h still with one pantograph. However, the system can then be used also with curvature radii below 800 meters [13].

3 CONTACT LINE SECTION ANALYSIS

3.1 Influence of sharp curves on the catenary system

Ideally it is possible to design the contact line section such as to minimize the vertical motion of the pantograph. Correspondingly, this will also reduce the dynamic response of the contact line rendering a continuous power supply and reduced wear. This optimization can be achieved by considering the system height of the catenary system, the tension force in both wires and the pole span length and the size of the pre-sag of the mid pole span. However, for sections with curves and other varying geometry the tension force will not be optimal for all pole spans. This is specially the case when the radius is low, which in Norway typically is below 800m. As mentioned earlier the droppers are used to achieve appropriate sag between each dropper as well as for the entire pole span. For a straight section it is advantageous to have long pole spans while in a sharp curve it is the curvature that decides the pole distance. This can introduce a considerable reduction in span length and thus changing the systems optimal parameters. Furthermore, the zig-zag pattern is in curvature designed by pull-off configuration of the registration arm and it is the straight contact line system crossing the curved track axis which creates the push-off as showed in Figure 7.

Figure 7. The zig-zag configuration in a curved section.

In curves a camber, canted track, is introduced to counteract the lateral tilting of the train from the centrifugal forces which act upon the train as it runs through the curves. The camber will tilt the pantograph correspondingly and will influence the interaction between it and the contact wire. This change in angle will introduce a vertical motion of the pantograph. I.e. it is from the pantograph position seen as an uplift of the cable rendering the upward motion of the pantograph. This is an unwanted motion which ideally would have been counteracted by a pre-sag of the contact wire. However, due to the tension which is set to correspond to longer pole spans within the section this is not possible. In fact, it is for the vertical droppers situated closest to the pole support an immediate risk to lose all tension leaving slack vertical dropper wires. This motion can be demonstrated by two figures showing the lateral positions of the contact wire along the pantograph head as the wire goes through the zig-zag pattern shown in Figure 4 and 7. In Figure 8 are the lateral motion outer points 1 and 2 shown on the pantograph head for the straight section zig-zag pattern.

Figure 8. The outer positions of the contact wire as introduced by the zig-zag pattern shown in Figure 4.

The effect of the contact point height on the pantograph as it goes through the zig-zag pattern in sharp curvature is included.
in the Figure 9. For both situations point 2 is situated at the pole supports, as point 1 is in the straight section while point 1 in the curved pole span is situated at the mid-span.

Figure 9. The outer positions of the contact wire as introduced by the zig-zag pattern in the curvature shown in Figure 7.

4 NUMERICAL INVESTIGATION OF THE CATENARY SYSTEM

To investigate the passage of a pantograph on a given section it is of interest to investigate the behaviour of the catenary system at different structural sections. The intention in the present study is to see how the changing geometry of sections with sharp curves will create dynamic implications for changing train velocities. The modelled section is located at Soknedal, Norway. The system here has been designed for 90 km/h while the surrounding sections have a design velocity of 130 km/h, an already allowed upgraded velocity.

The investigation will concentrate on the overhead contact system at hand, Tabell 54, as described. This system is today designed for 130 km/h on straight sections with a span length of 60 m. As the section of Soknedal progresses, it includes a sharp curve and a pass under a bridge where the catenary system is forced down due to low passage height. The latter is not specifically investigated in the current paper.

The data sampling is done on two models of Tabell 54, one which is modelled as a straight section with constant span length of 60 m and the other which is modelled “as built” at Soknedal, including upgraded tension forces. The contact wire and messenger wire now have upgraded tension forces of respectively 10 kN and 5 kN. The focus in the present paper will be on the change in dynamic response. This is predicted by time series evaluating the pre- and post-passage vibration as well as the uplift of the passage at representative positions along a pole span. The effects are also investigated by extracting the frequency content of sampled time series shown by spectral density plots.

4.1 Case study; railway section at Soknedal station

The railway section selected in this study is located just north of Soknedal station which is approximately 70 kilometres south of Trondheim. The section is part of Dovrebanen which runs from Oslo to Trondheim. The section was built with the catenary system Tabell 54, and it is 1301 meters long. The section is divided into twenty-six pole spans where the length of the spans varies between 40 and 60m. In the chosen railway section there is an initial curve with a radius of R = 1250m and a part with very sharp curvature, R = 350m. The spans in the sharp curvature have a length of 40 m whereas the straight section and the larger radius both have a length of 60m. These are irregularities which today significantly reduces the allowed running speed on the section to 90 km/h.

The geometry of the system has been found by making a correct global geometry of the track. The global coordinates of the track were used to establish global coordinates of mast positions and to the corresponding catenaries. The final numerical model is shown in Figure 10.

Figure 10. Final geometry of the Soknedal section used in the numerical model.

4.2 Material properties of the catenary system Tabell 54

The contact wire used in Table 54 is Rt 100 Cu. The cross sectional shape and area regulated for this contact wire is 100 mm², see also [13, 16]. The moments of inertia are given by: Iy=986.5 mm⁴ and Iz=839.2 mm⁴. Whereas the St. Venant number (torsion constant) is J=1511.5 mm⁴. The specific weight of this contact wire is 8.9 N/m, the Young’s modulus, E, is 124·10⁹ Pa [17]

The messenger wire used for this section is Cu 50/7. It has a circular cross section with a diameter of 9 mm, i.e. a cross sectional area of 60 mm², its specific weight is 4.46 N/m [13], the Young’s modulus, E, is 113·10⁹ Pa [16]

Finally, the droppers used for the catenary system on this section is Bz II 10/49, which has a circular cross section with the diameter of 4.5 mm, cross sectional area of 15 mm², its specific weight is 0.89 N/m [13], the Young’s modulus, E, is 100·10⁹ Pa [16].

4.3 Finite element model; catenary system and pantograph

The possibility for numerical modelling of the dynamic system has increased as computational power increases. Today, most studies of catenary systems uses a continuous finite element model including point springs, dampers and lumped masses for the pantograph model, see for example [17, 18, 19]. Special system properties have also been investigated for such systems, e.g. the modelling of the initial configuration of the catenary [20, 21] and also nonlinearities due to slackening of droppers [22].

Even though beam models are more complex compared to string models they include several important characteristics of which the catenary system is dependent on. This is especially important as train velocities are increased as shown by [23]. All wire components such as contact wire, messenger wire and droppers, are modelled by Timoshenko beam elements. As shown by Poetsch et al [24], it is not necessary to include shear deformation or rotary inertia effects when the wavelength in the contact wire is larger than 5 cm. In the current system is the wavelength found to be well over what is proposed. Thus, it is in theory sufficient to use Euler-Bernoulli beam elements, as reported used in similar catenary models [25]. However, due to numerical stability in the Abaqus analyses Timoshenko elements were more preferable and thus used in all the wire components.
The damping of the catenary systems can be assumed lightly damped [24]. Furthermore Wu Brennan [26] stated that the system can be assumed lightly damped for train speed up to 500 km/h. Thus, damping in the present catenary model is introduced as Rayleigh damping [27] with target value of 0.02 over a frequency span of 1-15 Hz.

In Abaqus [28] the Rayleigh damping is implemented such that the stiffness proportional contributions are only proportional to the strain stiffness, not including the geometric stiffness. This renders a damping of the catenary system, a wire system dependent on geometric stiffness, which is mostly mass proportional. This will lead to a correct damping description for low frequency motions whereas the higher frequency damping contributions will be underestimated. The dynamic response will therefore be expected to show tendencies of larger response for higher frequencies and subsequently longer decays. The model will still render good estimated displacements. This, since the motion is highly transient and with major contribution components due to lower natural frequencies.

The pantograph used in this study is modelled in a slightly simplified way as shown in Figure 11. The pantograph is modelled as a mass-spring-damper system, and describes the pantograph called WBL 88, produced by Schunk Nordiska AB, which is used in traffic at the selected railway section. The velocity dependent aerodynamic contact force is expressed by Equation 1, and contains static- and aerodynamic components as described specially for the use in Norway.

![Figure 11. Numerical model of the pantograph WBL 88 by Schunk Nordiska AB.](image)

\[ F_{\text{contact}} = 55 + 0.068 \cdot v^2 \]  

(1)

The pantograph model in Figure 11 includes \( m_1 \), which describes the two pan heads and a second mass, \( m_2 \), the mass of the pantograph arm. Both of these components are modelled as rigid parts. The springs, \( k \), and dampers, \( c \), describe measured values of stiffness and damping between the respective components. In the model from Schunk Nordiska AB, the damping between the arm and the main frame is included \( c_2 \), for downward motion and zero for upward motion.

4.4 Natural frequency estimations

The numerical model of the catenary system is a slender and flexible system with many similar components including small variations. This will give many similar eigenvalues from the eigenvalue analysis, and can be seen by the accumulations of modes around given frequencies. One way to interpret the estimated natural frequencies are by calculating the corresponding modal mass. Modes with large modal mass represent activated mass motion in the system, and are then good candidates for the fundamental frequencies.

The model shall be used as an interpretation tool. In the results from the eigenvalue analysis of strongly flexible structures the term fundamental frequency will not be as clearly defined as for civil engineering structures. This effect is further enhanced for the Soknedal section as this model also includes curvature, which makes the geometry of every span slightly different.

The first accumulation of frequencies is around 0.87 Hz, the second around 1.3 Hz, the third around 1.7 Hz and the fourth around 3.2 Hz. Frequencies in the area around 0.87 Hz is found to excite the spans with a length of 60 m while frequency for the 40 m spans are represented by 0.98 Hz, see also Figure 12. The first natural frequencies of the droppers are around 6.6 Hz.

A steady state analysis is done to evaluate change in structural frequencies imposed on the catenary system by the presence of the pantograph. The pantograph is then placed within a span and the contact wire is excited over a broad frequency band. The system analysis renders what will be referred to as catenary-pantograph steady state frequencies, or just steady state frequencies for short. The resulting first four frequencies of the steady state analysis are: 1.3, 2.7, 3.8 and 4.2 Hz respectively.

![Figure 12. Eigen modes corresponding to 0.87 Hz (upper), and to 0.98 Hz (lower).](image)

4.5 System analysis of the catenary model – Norwegian Tabell 54

To evaluate and extract the information available in the catenary system model, it is chosen to sample at different points on the structure. There are several points to choose from; it is important to cover different sections of the structure with different dynamic properties. One point of interest on the structure is at the support pole. This is a point where many failures often occur; especially the uplift value at this point is of importance. As described, due to the stiffness characteristics of the catenary system, it is expected that the largest increase in dynamic response will be at the midpoint, thus this point is also included in the analysis.
The intention is to investigate the system responds at varying curvature from else same tension configuration of the contact line section. Thus, the response is sampled at different train velocities to evaluate the influence of higher speed on the dynamic response. Generally, this is important information when considering upgrades or operational changes of existing systems. This could be a permanent increase in the allowed maximum train velocity or number of pantographs allowed.

The two systems, straight section and Soknedal station section are divided into sampling spans as given in Figure 13-14. The straight section includes six consecutive spans, all 60 m long, where each span includes two sampling points, (1-2) as shown in Figure 15. The Soknedal station section includes two parts with different span length for sampling. The initially straight part includes three 60 m spans with sampling points, (1-2) Figure 15, and the curved part which includes seven 40 m spans with sampling points, (3-4) also shown in Figure 15.

Figure 13. Spans used for sampling data, straight section Tabell 54.

Figure 14. Spans used for sampling data, Soknedal station section Tabell 54.

Figure 15. Sampling points on the two numerical models, 60 m span (upper), and 40 m span (lower)

4.6 Dynamic response of the catenary system Tabell 54

The time series sampled from a point on the catenary system is a complex history of different events. Some parts of the signal will include more information of the pantograph-catenary interaction system. Other parts of the time series will more or less be controlled by resonant response from one or two of the fundamental modes at the point of excitation. If information regarding the structural behaviour from forced vibration before the current point, or control of fundamental motion is sought, then selected parts of the time series should be used. The advantage of dividing the signal with possible various information contents is also supported by the findings in EUROPAC [29].

Here the entire sample is of a single passage shown in a mutual frequency time representation, Figure 16. Furthermore, it is from the characteristics of the displacement seen that there are two different dynamic processes present, one before and one after the passage.

The intention here is to overview the dynamic implications for higher speed in curvature, i.e. view the dynamic implications due to system changes from changing curve radius. Thus, it is for further results chosen to only present results from the vertical uplift displacements. The results will therefore have a weight on the lower frequency content controlled by the system stiffness. This can be compared to an analysis of the acceleration results which will introduce a weight on inertia controlled response, with corresponding higher frequencies.

The contact line section will in design have a total length dependent on the possible number of pole spans that can be included. Among other parameters is the number of pole spans depend on the loss of tension force at each pole support. This loss will be dependent on the lateral angel of the contact wire to the track axis at each pole. Thus, in sharp curves the tension force loss will be higher.

The parameters for the contact line system are initially designed for the straight section with spans of 60m. However, this creates a too stiff system for the sharpest curve. This is illustrated in Figure 17 where the uplift and corresponding displacement spectrum are shown for the straight section and R=350m for 90 km/h at point 1 and 3 (the mid-point).
This response can be compared to the excessive vibrations of the straight section as the train speed is increased to 130 km/h, Figure 18. The pre-passage vibration is here already significant and the post-passage is close to a standing resonant response.

It is interesting to observe that the Soknedal section model with the initial radius of 1250m has a large response at 90 km/h compared to both the straight section as well as the sharper curved segment of the same model; compare Figure 17 with Figure 19. This is partially due to the influence of the sharp curved segment as well as the transition segment included in the model. These will influence the section configuration and thus the sections natural frequencies. In the spectral plot in Figure 19 it can be seen that already at 90 km/h this response has a considerable resonant contribution while the two previous shown in the spectral plots of Figure 17 are dominated by a broad banded frequency response.

An important property is the uplift at the pole support. This uplift must be under a certain design value, which for this section should be below 50mm. In Figure 20 the three uplift plots for straight, R=1250m and R=350m, all at 160 km/h, are compared. It is seen that all three are under the limit value and thus initially ok. However, considering the post-passage it can also be seen a substantial resonant response which may be troublesome.

Finally, it is of interest to analyse the dynamic response of the segment which dynamically shows the best behaviour, R=350m. This segment can allow a train speed of 130 km/h as neighbouring contact line sections. Also the uplift for a train speed of 160 km/h is below acceptable limits whereas the dynamic response at mid-point is clearly resonant and also shows sign of beating in the post-passage response. Thus, it seems as the train speed of 160 km/h is close or over the limit for this section when considering the dynamic response at mid-span. At least if the train has more than one pantograph.

5 CONCLUSION

The dynamic behaviour of the Norwegian catenary–pantograph system, Tabell 54, has been examined numerically. The focus of the present investigation has been on the dynamic implication of higher speed on contact line sections with sharp curves. This is accomplished by three model segments with a radius of 1250m and 350m as well as a straight section.

It is seen that the different radius will influence the optimal configuration differently. Therefore sections with varying geometry will not have optimal designed behaviour. This is shown by the dynamic response especially at the mid-point of
different pole spans. The uplift is for the allowed speed of today, 90 km/h, within acceptable levels for all three segments. For the velocity of the neighbouring segments, 130 km/h, the straight section will show significant post-passage dynamic response, though within acceptable levels. However, the dynamic response of the contact line system is most likely above acceptable levels at mid-span for 160 km/h, especially for straight and the 1250m radius. The sharp curve has a dynamic response which is estimated to be close to the limit. All three segments have acceptable uplift response at the pole support; though the response of all three is resonant dominate as shown in the spectral density plots.

The implications of the investigations is however difficult to conclude solely on the dynamic response of the contact line. As demonstrated in the present investigation the exaggerate tension forces will in the sharp curve initiate excessive vertical motion in the pantograph due to the complete section design. This is partly the reason for the initiated vibration of the short and stiff pole span in the sharp radius. Thus, the sharp curves will initiate vibrations even for a short span. Since the span is shorter and stiffer than desirable the complete section will become too short and the wear will be higher than for the straight section and the vertical motion may also render loss of contact. This will diminish the possible increase of the allowed train velocity.

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