Dynamic behaviour of an existing railway catenary system for extreme low passage at exceeding design velocities

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ABSTRACT: An ever increasing demand for reduced travel time makes it important to exploit the full capacity of existing overhead railway catenary systems. This has become a pressing issue in Norway due to the fact that the maximum speed in many existing railway sections are only 70 or 90 km/h. In many places there is no plan to reconstruct the railway line. It is therefore important to investigate the static and dynamic behaviour of the pantograph-catenary interaction as the train speed is increased to ensure electrical and mechanical contact for higher speeds. Along the railway line there is several places where the contact wire height has to be decreased to pass under obstacles, such as bridges. This paper investigates the dynamic behaviour of an existing railway catenary system, named Tabell 54, for extreme low passage at exceeding design velocities. This has been done by running dynamic analyses on finite element models made of existing railway catenary systems with different gradients in the decrease of the contact wire height. It has been found that the dynamic response of the examined catenary system due to change in contact wire height starts to increase somewhere between 130 and 200 km/h. The dynamic response is also found to increase with increasing gradient between the same velocities.

KEY WORDS: Catenary systems; Contact wire; Dynamic response; Norwegian railways; Pantograph-catenary interaction; Existing railway catenary; Spectral analysis; Numerical simulations.

1 INTRODUCTION

The improvement of the structural understanding during the life span of essential infrastructures is an important problem to address. This is partly due to the situation of an ever increasing number of infrastructures reaching their final stage of design life, and partly due to changing loads and non-fulfilment of maintenance, rendering physical signs of wear and tear.

In this study a part of the Norwegian Railway called “The Dovre line” is investigated. This is the main railway line between Oslo and Trondheim. The part investigated was electrified in 1970, and was built on piecework. At the investigated section the contact wire height is lowered to pass under an existing bridge. The contact wire height is thus reduced from 5.6 m to 5.15 m. The design speed is between 70 and 90 km/h, depending on the topology. Due to these low speeds improvements are sought to be able to increase the speed.

The essential property of the interaction between the catenary system and the pantograph for the electric railways is to ensure supply of electricity to the train. This interaction is a coupling of two non-linear dynamic systems[1]. The induced wave motion from this interaction in the catenary system is extremely complex, and is influenced by many parameters such as the span length, the mass of the wires, the tension in the wires, the dropper spacing and the design of the supporting structures. The understanding of this interaction is mandatory to develop existing catenary systems dynamic behavior where performance improvements are sought [2]. As the velocity of the train is increased, the importance of the dynamic behaviour of the railway catenary system is also increased[3]. 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. The catenary system investigated is design for much lower speeds. At design speed the behaviour of the catenary system is for practical purposes quasi-static as the train passes. However, numerical simulations show that as the velocity is increased above the design speed the dynamic behaviour also increases until excessive vibration response is observed.

A change in the gradient of the contact wire height will at higher speeds give a significantly larger dynamic behaviour than if the gradient was null. This is because of differences in the geometry of the catenary system due to gravity, elasticity properties of the catenary system and the rapid decent of the pantograph.

A result of a too extensive dynamic response of the catenary system is increased wear and extensive challenges regarding an introduction of multiple pantographs on the trains[3].

In this study the increase of dynamic behaviour due to rapid extreme lowering of contact wire height is investigated as the speed is increased above design speed. The present study evaluates the dynamic coupled system between the catenary system and the pantograph. This includes 3D finite element modelling of a full length section of the existing catenary system. The model is used to investigate the vertical displacements of the contact wire along the whole section.

2 RAILWAY CATENARY 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](image1.png)

Figure 1. A discretization of the catenary system. SH is the system height, and L is the length of one span.

![Figure 2](image2.png)

Figure 2. The bracket, the registration arm and the pole at an existing railway section in Norway.

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 [4] 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.

![Figure 3](image3.png)

Figure 3. The tensioning equipment in use at the existing railway section called Soknedal section.

2.1 Norwegian railway catenary systems

The main existing catenary systems in Norway are called Tabell 54, System 35, System 20 and System 25. The three latter are the only systems used in new Norwegian railway sections[5]. The main difference between these systems 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. 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[5].

The first system, Tabell 54, is widely in use in the existing railway systems, also in locations where there is yet no plan to change the railway sections. This system was originally designed for train speeds of maximum 90 km/h. The tension forces were then 6.1 kN in the contact wire and 4.9 kN in the messenger wire[6]. These tension forces were changed to respectively 10 kN and 5 kN to enable an increase in train velocity to a maximum of 130 km/h.

3 THE NUMERICAL MODELLING OF THE CATENARY SYSTEM

The dynamic behaviour of the catenary system Tabell 54 is investigated for current and increased velocities. For this investigation four three-dimensional finite element models of different railway sections in Ahaus were made. The first model is of a straight section of Tabell 54 and is 1500 metres long. This model will henceforth be called Model 1, and is shown in Figure 4. The three other models are also of a straight section also with a length of 1500 metres, but they include a decrease of the contact wire height over a length of 360 metres. In the second model the decline of the height goes from 5.6 to 5.3 metres. In the third model the decline is from 5.6 to 5.15 metres and in the fourth model the decline is from 5.6 to 4.74 metres. These three models have been termed Model 2, Model 3 and Model 4, and are respectively shown in Figure 5, Figure 6 and Figure 7. The third model has the same decline as an existing section called Soknedal section, which is located in The Dovre line. The decline in the second model and the fourth model has the maximum gradient allowed for sections with train speeds of respectively 200 km/h and 70 km/h.

![Figure 4](image4.png)

Figure 4. The finite element model of the straight section, Model 1. The height is scaled by a factor of sixty.

![Figure 5](image5.png)

Figure 5. The finite element model of the straight section with decrease from 5.6 to 5.3 metres, Model 2. This has the maximum gradient for a train speed of 200 km/h. The height is scaled by a factor of sixty.
The dynamic analyses have been performed with train speeds of 90, 130 and 200 km/h. The first speed, 90 km/h, was chosen because it is the running speed at an existing railway section which has the same gradient as in Model 3. The next, 130 km/h is the maximum allowed speed at the catenary system Tabell 54. And the last, 200 km/h, is a speed which may be assumed achievable to reach on straight railway sections in Norway in the future.

3.1 The catenary

The contact wire, the messenger wire and the droppers are modelled with three-dimensional deformable beam elements. To ensure a stable numerical solution Timoshenko beam elements are used. Euler-Bernoulli beam elements could also have been used, but the use of both elements will according to Poetsch, et al. [1] give negligible effects on the results. The corresponding vertical natural frequencies of the numerical models have been found, and this has shown that there exist many different estimated frequencies. Thus it is chosen to present the five frequencies which are representative for the first areas of estimated frequencies. These are presented in Table 1.

Table 1. The first five natural frequencies found from analyses of the numerical models

<table>
<thead>
<tr>
<th>Natural frequencies</th>
<th>1st</th>
<th>2nd</th>
<th>3rd</th>
<th>4th</th>
<th>5th</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency [Hz]</td>
<td>0.86</td>
<td>1.05</td>
<td>1.7</td>
<td>2.5</td>
<td>3.0</td>
</tr>
</tbody>
</table>

The damping of the wire system is introduced by the use of Rayleigh damping[7], which gives a mass- and stiffness proportional damping matrix. This kind of damping is used in several works on catenary systems[8]-[10]. The damping coefficient used is 2 \%.

3.2 The pantograph

There are mainly four different pantographs in use in Norway today. These are Schunk WBL 85, Schunk WBL 88, Schunk WBL88 AT and RM374. The pantograph WBL 88 has been used for this study due to it is the most common pantograph in use at the investigated section. The pantograph is modelled as a mass-spring-damper model in accordance with a model received from the manufacturer Schunk Nordiska AB. This model is illustrated in Figure 8. This simple model can only have two natural frequencies, and the first is found to be 4.7 Hz.

![Figure 8. The numerical model of the pantograph, WBL 88.](image)

The pantograph model in Figure 8 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 spring, \( k \), 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 \( c_s \), for downward motion and zero for upward motion.

4 RESULTS AND DISCUSSION

There have been performed several dynamic analyses on the four numerical models. Twelve sampling points have been chosen for each model. These points are located in the middle of the spans and at one of the supports in six different spans, A to F, as shown in Figure 9, Figure 10 and Figure 11.

![Figure 9. The sampling were done in these six spans, A to F, in the analyses done on Model 1.](image)

![Figure 10. The sampling was done in these six spans, A to F, in the analyses done on Model 2, Model 3 and Model 4.](image)

The main focus of this study has been on the dynamic response at mid span, although the most common focus in the literature is to investigate the response in the catenary at the support. This has been chosen because the dynamic response in mid span is larger than at the support, and thus, excessive
vibrations will be apparent at lower train velocities, and
dynamic effects due to a change in gradient may be seen more
clearly. The dynamic response have been investigated by
regarding the vertical displacement as a train approaches,
passes and have passed the midpoint of a span. The maximum
uplift has been extracted from the analyses for train speeds of
90, 130 and 200 km/h for span A to F. The mean maximum
value and the standard deviation of the uplift for the six spans,
A to F, is found to be increasing when the speed goes from 90
to 130 km/h. But from 130 to 200 km/h the standard deviation
is the only one increasing. The mean maximum values of the
uplift and the standard deviation of the maximum uplift in
span A to F are shown in Figure 12 for Model 1, 2, 3 and 4.
The gradient of the decrease of the contact wire height
increases with increasing model numbering. Thus, it can be
seen that the maximum vertical displacement in mid span
increases for an increasing gradient.

Figure 12. The maximum uplift in the middle of the spans A
to F displayed with the mean value and standard deviation for
Model 1, 2, 3 and 4. Values have only been found for train
speeds of 90, 130 and 200 km/h.

The mean contact force and the standard deviation of the
contact force have been extracted for all these analyses. The
values were found to be of the correct magnitude compared
with given measurements at 90 and 130 km/h. This indicates
that the contact force is of the correct magnitude for 200 km/h
as well.

By looking at the vertical displacement and the
 corresponding spectral density in point C1 the dynamic
 response at mid span has been more thoroughly investigated.
The only difference in the response between the four models
for train speeds of 90 and 130 km/h is a difference of the
maximum displacement. It was found to increase
approximately linearly from Model 1 to 4 with 10%. At these
velocities there is not found any particular difference in the
dynamic response. When the speed was increased to 200 km/h
there was found both static and dynamic differences between
the models. For the three different train speeds there have
been in general found that the maximal vertical displacement
in C1 increases as the speed is increased, mostly between 90
and 130 km/h, but also some between 130 and 200 km/h. This
can be seen when comparing responses given in Figure 13,
Figure 14 and Figure 15. For all the four models the response
at 90 km/h is found to be quasi-static, but already with a train
speed of 130 km/h the dynamic response is found to be
significant. This can be seen directly from the plots of the
displacements where at 90 km/h the response is only a peak
when the train passes underneath the regarded position, which
clearly shows that the response is not dynamic. At 130 km/h
the system oscillates about its equilibrium position with
significant amplitude, which decreases with time due to
damping in the system. The spectral density of the vertical
displacement for a train speed of 90 km/h shows also that the
response is mostly influenced by static contributions, and thus
confirms that the response is quasi-static, Figure 16. From the
spectral density of the displacement for a train speed of 130
km/h the dynamic response is confirmed by the total increased
response compared with at 90 km/h, and especially the high
response close to the first natural frequency, see Figure 17.
The peak of the response is found at a frequency slightly
below what was found as the natural frequency in the
frequency analyses performed. But after investigating the
response of the catenary around this slightly lower frequency
there is found that this response looks like a stationary half
sine wave in one span after the train has passed, and thus the
first natural frequency. It is possible that the natural frequency
is lowered due to a change in the effective stiffness/mass ratio
as the train passes the section. And because it is so close to the
estimated natural frequency, it continues to oscillate with this
frequency.

In the analyses with a train speed of 200 km/h there is
oscillations after the train has passed. The shape of the
oscillations shows sign of beating due to a combined response
of two very close frequencies. The corresponding spectral
analysis shows that the response is most influenced by the
dynamic response in a narrow area around the first natural
frequencies. The damping ratio for this frequency is found
with the half-power bandwidth method to be approximately
2% for the analyses of all the models with train speed of 200
km/h. This is the same damping value which was introduced
for the first natural frequency in the numerical model.

Figure 13. The vertical displacement of point C1 in Model 1
as a train with a speed of 90 km/h passes the modelled section.
For a more comprehensive investigation of the dynamic response as the train speed is increased the results from the analyses with a train speed of 200 km/h for the four models have been compared. The maximum vertical displacement in these analyses can clearly be seen to increase with steeper gradient. This increase is presented in Table 2 both by the actual maximum vertical displacement, and the increase compared with the displacement from Model 1 in per cent. These results can also be seen by comparing the plots in Figure 15, Figure 19, Figure 20 and Figure 21. From the corresponding spectral analyses there is found that the dynamic response also increases as the gradient steepens by comparing the magnitudes of the spectral density. This can be seen by comparing values of the spectral density from Model 1 to 4, shown in Figure 18, Figure 22, Figure 23 and Figure 24.
Table 2. The increase of the maximum vertical displacement as the gradient is increased for train speed of 200 km/h.

<table>
<thead>
<tr>
<th>Model</th>
<th>Gradient in decrease [m/m]</th>
<th>Max. vertical displacement with train speed of 200 km/h [mm]</th>
<th>Increase of max vertical displacement compared with Model 1 [%]</th>
<th>Max. spectral density</th>
<th>Increase of spectral density compared with Model 1 [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.000</td>
<td>80</td>
<td>0</td>
<td>4481</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>0.001</td>
<td>84</td>
<td>5</td>
<td>5651</td>
<td>26</td>
</tr>
<tr>
<td>3</td>
<td>0.0015</td>
<td>87</td>
<td>8.75</td>
<td>6004</td>
<td>34</td>
</tr>
<tr>
<td>4</td>
<td>0.0029</td>
<td>93</td>
<td>16.25</td>
<td>6991</td>
<td>56</td>
</tr>
</tbody>
</table>

Figure 19. The vertical displacement of point C1 in Model 2 as a train with a speed of 200 km/h passes the modelled section.

Figure 20. The vertical displacement of point C1 in Model 3 as a train with a speed of 200 km/h passes the modelled section.

Figure 21. The vertical displacement of point C1 in Model 1 as a train with a speed of 200 km/h passes the modelled section.

Figure 22. The corresponding spectral density of the vertical displacement of point C1 in Model 2 as a train with a speed of 200 km/h passes the modelled section.

Figure 23. The corresponding spectral density of the vertical displacement of point C1 in Model 1 as a train with a speed of 200 km/h passes the modelled section.
Figure 24. The corresponding spectral density of the vertical displacement of point C1 in Model 1 as a train with a speed of 200 km/h passes the modelled section.

5 CONCLUSION

The dynamic behaviour of the existing Norwegian catenary system, Tabell 54, has been investigated, to determine at what train speeds dynamic response can be expected, and what dynamic effects a decrease of the contact wire height induces for different speeds. Dynamic analysis with three different train speeds, 90, 130 and 200 km/h have found that dynamic response of significance is found already at 130 km/h both for sections with and without a decrease of the height. The specific dynamic effects of a contact wire height decrease is found by performing dynamic analyses on four numerical models with different gradients of this decrease. It has been found that additional dynamic effects from this decrease are not present at 130 km/h, but are significant at 200 km/h. The dynamic response for the model with the steepest contact wire height decrease is around 50% larger than the model with no decrease. This indicates that at some speed between 130 and 200 km/h the additional dynamic effects due to this decrease are of great importance. To better control the dynamic effects due to this decrease a more thoroughly study should be done with speeds between 130 and 200 km/h.

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