Abstract:
Optical fibers with Bragg grating sensors can be used to measure dynamic strains in mechanical systems. The inherent electrical insulating properties of optical fiber measurement systems are of great advantage when working on high voltage systems. In the present work such sensors are employed to detect and measure vibrations on overhead power lines. Vibrations may over time cause fatigue damage, and especially on large fjord crossings mechanical failures may have dramatic consequences. In the present study results obtained from a full-scale tests on a 300 kV overhead power line are presented. Numerical simulations of the same power line have also been done, and comparisons between measurements and simulations are presented.

1 Vibrations on Overhead Power Lines
Vibrations and oscillations of overhead power lines is a common phenomenon, and can roughly be categorized in three groups: aeolian, galloping and subspan oscillations.

Aeolian vibration is caused by vortex shedding behind the conductor, where the frequency of vortex shedding is given by the Strouhal relationship [1]. Aeolian vibration occurs in low to moderate winds, and has an amplitude comparable to the conductor diameter. The main danger of aeolian vibration is fatigue damage on the conductor, limiting the safe life-span of the conductor [4].

Symbol

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>ε</td>
<td>Strain</td>
</tr>
<tr>
<td>ε_B</td>
<td>Bending strain</td>
</tr>
<tr>
<td>E</td>
<td>Modulus of elasticity</td>
</tr>
<tr>
<td>A</td>
<td>Cross section of conductor</td>
</tr>
</tbody>
</table>

TABLE 1. Nomenclature:

Symbol

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>Second moment of inertia</td>
</tr>
<tr>
<td>EA</td>
<td>Axial stiffness</td>
</tr>
<tr>
<td>EI</td>
<td>Bending stiffness</td>
</tr>
<tr>
<td>R</td>
<td>Radius of curvature</td>
</tr>
<tr>
<td>κ</td>
<td>Curvature</td>
</tr>
</tbody>
</table>

Vibration Measurements and Analysis of Overhead Power Lines
Using Fiber Optical Sensors

Svein Magne Hellesø, M.Sc.
Dept. of Electrical Power Engineering, Norwegian University of Science and Technology (NTNU)
O. S. Bragstadspl 2, N-7491 Trondheim, Norway

Bjørn Skallerud
Professor, Ph.D.
Dept. of Applied Mechanics, Thermodynamics and Fluid Dynamics, Norwegian University of Science and Technology (NTNU)
Kolbjørn Hejes vei 2, N-7491 Trondheim, Norway

Leif Bjerkan
Senior Scientist, Ph.D.
SINTEF Electronics and Cybernetics
O. S. Bragstadspl 2A, N-7465 Trondheim, Norway

Magne Runde
Associate Professor, Ph.D
SINTEF Energy Research
Sem Sælandsvei 11, N-7465 Trondheim, Norway
Galloping occurs in medium to high winds and if ice or snow builds up on the conductor and creates an aerodynamically unstable shape. This can give large forces and moments on the conductor, and large amplitude low frequency vibrations can build up rapidly. The most violent galloping occurs if the torsional eigenfrequency of the line is close to one of the lower eigenfrequencies for vertical vibrations of the line. The main danger from galloping is mechanical failure of the line or tower, and electrical spark-overs failures if live conductors clash.

Sub-span oscillation is a phenomenon that occurs on bundled conductors, where the vortex shedding wake hits one of the other conductors and this conductor starts to oscillate.

Vibration damping on overhead power lines is dependent on which kind of vibration that is targeted. Aeolian vibration is damped by attaching devices that extract energy from the line. A variety of devices have been developed and used, but today the most widespread device is the Stockbridge-damper or variations of this. This damper consists of a short length of wire with masses on the ends, and a clamp in the middle for attachment to the conductor. If the conductor vibrates, this movement will also set the wire vibrating, and if the frequency of vibration of the conductor is close to the eigenfrequency of the damper, then large deflections of the masses will occur and dry friction between the strands in the wire will consume energy, and thus damping the vibration.

For suppression of galloping the main principle is to try to alter the torsional eigenfrequency so that it does not coincide with the vertical eigenfrequency. This can be done with torsional dampers or detuners.

Subspan oscillation is mainly damped using space dampers, which are spacers with flexible rubber-damped joints fitted between the conductors.

2 Measurements of Vibrations
There is a wide range of measurements systems developed and used for measuring vibrations on overhead power lines. The first systems were based on mechanical devices where the vibration activity is recorded graphically on paper. More recent systems have been based on measuring the deflection of the conductor close to fixed points of the span, for example near suspension clamps. A drawback of these systems is the location at which the vibrations are measured. Most systems are limited to measuring vibrations close to suspension points, as the systems measure deflection, and thus need a fixed reference. This creates problems when the span is damped using (in most case) end-span damping, where dampers are placed in groups close to the ends of the span.

If vibrations are measured at the suspension points, only vibrations reaching the this point are included. The vibration level in the mid-span between the end-span damping could still be significant, as vibrations can occur in the mid-span with the outmost dampers on each side acting as reflection points. High frequency vibrations can then occur undetected in the mid-span, and induce fatigue damage on the conductor in the mid-span.

The underlying objective for the work described here is to develop a method of measuring vibrations on an arbitrary location in long spans, in particular on long fjord crossings.

3 Fiber Bragg Gratings

In the recent years there has been a significant development of fiber optics and fiber optic sensors [6]. One of these recent developments is the fiber optic Bragg grating.

A fiber optic Bragg grating is an area of fiber where there is a periodic variation of the refractive index of the core of the fiber. This variation of the refractive index is made using a photo-inscription process to create the desired pattern in a doped fiber core. When light from a broadband source (containing light in a range of wavelengths) impinges on such a grating, a strong reflection occurs for the light wavelength matching the period of the grating. This wavelength is the Bragg wavelength $\lambda_B$. When the fiber with the Bragg grating is stretched or compressed, the period of the Bragg grating changes proportionally to the change of strain in the fiber. The wavelength of reflected light changes in proportion to the change of the period of the Bragg grating. By tracking the wavelength position for the peak in reflection intensity, changes in the strain of the fiber can be measured. In this way a fiber Bragg grating can be used as an optical strain gauge.

The use of fiber Bragg grating sensors in vibration measurements on high voltage power lines is motivated by the characteristics of fiber optics and fiber Bragg gratings. Optical fibers are immune to interference from electromagnetic fields, and are well suited for use in high voltage, high current environments. In addition the fiber cable with the integrated Bragg grating can be used as a communication fiber, allowing the instrumentation to be placed well away from the actual measurement position. This facilitates measurements on long spans, and winding the fiber cable around the conductor to take it to a tower and down to ground potential.

There are several instruments for measurements with fiber Bragg grating sensors available commercially. For this experiment instruments made in house have been used. The prin-
The principle of operation is shown on Figure 1.

The key part in the instrument is a laser with a tuneable output wavelength, in this case a distributive Bragg reflector (DBR) laser [5]. The wavelength of the laser can be tuned over the wavelength range from 1549.0 nm to 1554.2 nm in discrete steps, controlled by a digital-to-analog converter board and a custom-made application in LabView. The two photo detectors measure the output power of the laser and the intensity of the reflected light from the fiber Bragg grating. The position of the peak in the reflection spectrum is determined using peak-finding algorithms in LabView. The position of the peak is kept as the final result from each wavelength sweep.

The idea behind using fiber Bragg grating sensors to measure vibrations is to measure the change in bending strain when the line vibrates. The bending strain is proportional to the local curvature of the line, given by (1).

\[ \varepsilon_B(y) = \frac{1}{R}y = \kappa y \]  (1)

Here \( \varepsilon_B \) is the bending strain, \( y \) is the distance from neutral axis, \( R \) is the radius of curvature and \( \kappa \) is the curvature. Obviously the strain of the line is also influenced by changes in the tension and temperature of the line.

4 Description of Field Experiment

The purpose of this experiment was twofold: the first was to have a full scale test of the dynamic response of a power line to validate a finite element model of a power line. The second purpose was to get a significant signal amplitude from the fiber Bragg grating sensors during controlled excitation.

The span used in the experiment is close to a substation of the Norwegian national grid, and operates at 300 kV. An overview of the span is shown in Figure 2.

The span length \( L \) is 158 m, the height difference \( H \) is 8 m, and the horizontal tension is 16750 N. The line type is Parrot, an aluminum conductor reinforced with a steel core. The conductor is made up of three layers with one, six and 12 steel wires with a diameter of 2.55 mm, and three layers with 12, 18 and 24 aluminum wires with a diameter of 4.25 mm. The mass of the line was 2.878 kg/m, and the axial stiffness \( EA \) of the line was 7.40 \( 10^7 \) N/m. The bending stiffness \( EI \) of the line, assuming no friction between the wires, was 68.8 Nm².

The fitting of the fiber Bragg grating sensors to the line were done to test different methods of fixing of the sensors to the line and to validate safe and continued operation on live high voltage lines. The sensors had been mounted for over a year when this experiment was done, and their locations are shown in Figure 3.

Fiber Bragg grating sensors

The distance \( L1 \) is 19.6 m, \( L2 \) is 5.0 m, and \( L3 \) is 4.8 m. Two different methods of attaching the sensors to the line were tested out. One method, illustrated on Figure 4, used two clamps with an interconnecting aluminum rod between, where the part of the fiber with the Bragg grating being fixed in place in a groove along the rod. The entire assembly is
then clamped onto the conductor.

The other method, illustrated on Figure 5, used a similar rod and with the fiber and grating fixed in place in a groove along the rod. The rod was then preformed to fit on one of the outer wires of the conductor, and was glued to the conductor.

The sensors BG1 and BG2 were of the clamp type, and the fiber Bragg grating sensor was placed underneath the conductor. The sensor BG3 was of the tube type, and the fiber Bragg grating sensor was placed on the upper side of the conductor.

The experiment consisted of applying a given load to the line at a distance \( L_m \) of 62.6 m from the highest end of the power line, see Figure 2. The load was applied by throwing a rope over the line, and hanging weights of known mass from the rope. The load was released instantly using a suitable mechanism to create an impulse load on the line. During this the response from the fiber Bragg grating sensors was recorded, and a digital video camera was used to capture the resulting movement of the line, focusing on a small area around sensor BG2. This video recording was later transferred to a PC, and the horizontal and vertical position of sensor BG2 was determined for the experiment. The frame rate for the video was 25 frames per second, and the fiber Bragg grating sensors were sampled at 100 Hz. The noise level of the fiber Bragg grating wavelength measurements with used instrumentation is in the range of 0.2 pm to 1 pm.

5 Numerical Simulations

The finite element program used in the simulations herein is a tailor made software for the offshore industry (three-dimensional frame and shell structures, risers and pipelines) [3]. It can handle large displacements and rotations, based on a version of the co-rotated kinematic approach with the Green strain as deformation measure at local element level. Advanced cyclic plasticity models for stress resultant based plasticity are implemented. Several element types are available. A beam type element is used in the present work. The semi-discrete dynamic equilibrium equations are solved by means of an implicit Newmark time stepping scheme with the parameters \( \alpha, \beta \) and \( \gamma \) set to the values 0, 0.25 and 0.5.

The span was represented by beam elements with a length of five meters, but with shorter elements with a length of one meter at the sensor locations.

6 Results from Field Experiment

Two different loads were applied, one of 139.2 kg, and one of 251.8 kg. The vertical and horizontal position for the BG2 sensor derived from the video recordings for this two loads are shown in Figure 6 and Figure 7.
cation of the first two positive peaks on Figure 6.

The response from the fiber Bragg grating sensors for the two different loads are shown in Figure 8 and Figure 9 respectively.

As can be seen the frequency for strains in these two cases are similar, but their magnitude is different. The initial strain reduction is due to the drop in tension in the line when the load is released. The subsequent spike in strain is probably caused by the first transversal wave reaching the sensor, giving increased curvature at the sensor location.

The calculated strain for sensor BG2 is similar to the strain for BG1, and is not displayed here. The strain for BG3 shows a
marked difference, and is displayed on Figure 12.

The initial strain reduction due to reduced tension is also evident here. This reduction of strain because of reduced tension should be essentially equal for all three sensors, but the reduction in strain for sensor BG3 is smaller. The reason for this is not clear.

For all three sensors there is an initial rapid variation in the strain, which can be seen more clearly on Figure 13, which shows the strain for sensor BG1 in the first second after release of a load of 251.8 kg.

The period of this variation of strain is around 0.055 seconds, which corresponds to a frequency of around 18 Hz. The reason for this rapid variation in strain is not clear, but it could be longitudinal elastic wave propagation in the conductor.

7 Comparison of Experiment and Simulations

The main criterion for having a suitable model of the power line is an agreement between the measured and simulated global response for the applied load. Simulations of the response of the power line after applying and releasing a mass of both 251.8 kg and 139.2 kg were done, and the vertical position of the point corresponding to the sensor BG2 was compared with the measured position of this sensor. These comparisons are shown in Figure 14 for a load of 251.8 kg, and in Figure 15 for a load of 139.2 kg.

The current finite element model seems to be a good representation of the power line, and the initial response seems to correspond well to the measured response. Some discrepancies show up after a few periods, which are due to effects of the surrounding structure. During the experiment other lines, attached to the same tower and traverse, were also exited and started to vibrate, hence energy is dissipated into other parts of the system. This is not accounted for in the simulations.
8 Discussion
The measurements from the fiber Bragg grating sensors show that the use of this kind of sensors is well suited for measurements of dynamic loads on overhead power lines. The interpretation of some of the characteristics of the measurements is still unclear.

The current finite element model displays most of the characteristics of a vibrating power line, but further work should give improved match between simulated and measured global response. Especially the influence of the surrounding structure on the vibration characteristics should be better understood.

The main work remaining is comparing the measured strains with strains derived from the finite element model. This will be done in the immediate future.

9 Conclusion
The use of fiber Bragg grating sensors for measurements of mechanical loads on overhead power lines is validated. The high sensitivity the sensors results in measurements with a great deal of high frequency contents, and this complicates the analysis of the measurements.

References