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MEASUREMENTS ON AEOLIAN VIBRATIONS ON A 3 KM FJORD CROSSING WITH FIBRE-OPTIC BRAGG GRATING SENSORS

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Summary

An installation of a system for vibration measurements using fibre-optic sensors on a long 420 kV overhead transmission line span is described. The sensors are installed from the bottom of the span towards one of the anchoring towers, in order to detect vibrations in the mid span and outside of the end span damping arrangements. The measurement system has been in continuous operation for 6 months during the winter 2003. A great number of vibrations were detected in the frequency range 3-30 Hz in addition to low frequency oscillations. The vibration statistics in terms of frequency and amplitude distributions was obtained. The vibration amplitudes were found not to be excessive, indicating that the damping of the span is satisfactory, with low risk of fatigue damage.

Keywords

Overhead line – Aeolian vibration – Fibre-optic – Sensor – Bragg grating – Measurements – Weather

1. Introduction

Aeolian vibrations is a well known phenomenon that can occur on almost any transmission line at any time and are induced by low to moderate winds. In general these vibrations may become problematic in flat landscapes with steady winds. In addition the phenomenon is present for spans crossing fjords and valleys where high conductor tension is employed. These, mainly vertical oscillations, are characterized by small amplitudes (comparable to the line diameter) and typically in a frequency range 3 - 100 Hz depending mainly on the wind velocity and the conductor diameter. These vibrations may with time result in fatigue damage to the conductor in particular at the suspension clamps as well as damage to aircraft warning balls attached to the line. Available techniques for characterization of these vibrations on power lines in operation are rather limited.

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With the high tension in the fjord crossing conductors, the vibration amplitudes can increase to levels where damage will occur, and additional damping is therefore required for such installations. Usually the dampers are installed at the end of the span, and the effect of the damping is assessed by measuring the vibration amplitude close to the suspension points [1]. Measurements of vibration amplitudes close to the ends will not detect vibrations in mid span of long crossings. In addition for long fjord crossings the conductors are attached to anchoring towers with dead end strings, so there are no suspension points for measuring vibration. Thus there is a need for a method that can be used to measure vibrations at any location of such spans, which allows measurements when the line is in operation.

A vibration measurement system based on the use of fibre-optic sensors has been developed and tested in small-scale field trials [2]. The present work reports on the installation of such a system on a 3 km long overhead transmission line fjord crossing. A summary of the experience and results obtained over the test period will be presented.

2. Fibre Bragg grating sensor system

Fibre optic sensor technologies are finding growing applications in the area of monitoring civil structures. In large part due to advances in fibre telecommunications technologies, the costs for fibre sensors have been dropping steadily, and this trend will continue. Measurement capabilities and system configurations that are not feasible with conventional technologies are now possible with fibre sensors, enabling previously unobtainable information on structures to be acquired. Optical fibres may now find an important use in structural sensing because of their small dimensions, flexibility, immunity to electromagnetic interference, safety against hostile environments, and capability of remote sensing among others.

The most attractive fibre-optic sensor is the Fibre Bragg Grating (FBG), [3] which is sensitive to strain in any form, that is from bending, stretching or temperature change. Bragg gratings can be inscribed directly in a standard optical fibre at any position, and several of them can be configured in series in one fibre or in parallel on different fibres and interrogated from the same light source enabling flexible sensor configurations. The length of a FBG is typically around one centimeter and a series of Bragg gratings works as a set of discrete point sensors at chosen positions. Standard telecommunication fibre is used, and the fibre acts as both discrete sensing elements and as transport of signals. Since FBG's are conveniently used in reflection, the light source and detection device can be instrumented in one unit. Thus, all instrumentation is located in the same place. Low transmission losses of optical fibres enable remote sensing, i.e. the sensors may be placed several kilometres away from the instrumentation. These sensors have recently been successfully used in monitoring loads on various structures like bridges, ships and composite material devices.

Optical fibre technology has an advantage in high electric power environments in view of their immunity to electromagnetic fields, but low weight, small dimensions, explosion safety and possibility to transfer signals over long distances make them also attractive. Therefore, optical FBG sensors are now introduced as promising tools for the electric power market.

The idea behind using fibre Bragg grating sensors for vibration measurements is that when a conductor vibrates, the curvature of the conductor changes, leading to a change in the strain. From basic mechanics it is known that the bending strain in a beam undergoing deformation into a shape with a curvature κ is given by:

$$\varepsilon_{bend}(x,t) = \kappa b \approx b\frac{d^2 y(x,t)}{dx^2} \tag{1}$$

where ε_{bend} is the bending strain, b is the distance from the neutral plane and y the vibration amplitude at the position x and time t.

It can be assumed that the shape of a vibrating conductor is in the form of harmonic standing waves and can be expressed by the following deflection from the static shape:

$$y(x,t) = A\sin\left(\frac{n\pi x}{L} + \phi\right)\cos\left(\frac{cn\pi t}{L}\right) \tag{2}$$

where A is the maximum vibration amplitude, n is the mode number, L is the length of the conductor, c is the transversal wave velocity of the conductor, and φ is an arbitrary phase that may depend on the end conditions and the presence of damping devices. Combination of (1) and (2) yields:

$$\varepsilon_{bend} = -bA\left(\frac{n\pi}{L}\right)^2 \sin\left(\frac{n\pi x}{L} + \phi\right)\cos\left(\frac{cn\pi t}{L}\right) \tag{3}$$

The response of a FBG sensor is a shift in wavelength of the reflected light which is directly proportional to the induced strain. Thus, the bending strain induced by vibrations can be tracked directly by measuring the response of the FBG sensor. Note that the strain is proportional to the frequency squared ($f=n\cdot f_0$ with f_0 the frequency of the fundamental mode) due to the shorter wavelength at higher frequencies. This gives a measurement system based on measuring the bending strain an increasing sensitivity at higher frequencies. The strain is also dependent on the location of the strain sensors with respect to the nodes and anti-nodes on the vibrating conductor, as (3) shows. Furthermore, during the installation, the sensors were positioned at the top of the conductor where b=D/2 and D the conductor diameter.

3. Installation of the sensor system

The measurement system was installed on a 420 kV overhead transmission line crossing the Glomfjord, just south of Bodø in northern Norway. The span is 2910 m long. The conductor is of the type 912-Teist, with a diameter of 56.7 mm and a mass of 6.44 kg/m. The horizontal tension in the conductor is 385 kN, which is about 47% of the breaking load (catenary constant H/w=6000). The span is shallow, with maximum sag (relative to a straight line between the anchoring points) of 175 m. The vertical distance between the anchoring points is 175 m. A sketch of the span is given in Figure 1.

The high tension results in a very low internal damping in the conductor, and with the given climatical and topographical conditions, the span is very susceptible to wind-induced vibrations. A combination of Bretelle and Stockbridge dampers was initially installed at both ends. Still however, the span was troubled with vibrations, as described in [4]. In parallel with the installation of the measurement system even more dampers were installed. Twelve groups of additional Stockbridge dampers were installed along the entire span to obtain mid span damping of the fjord crossing. Each group consists of two to four dampers.

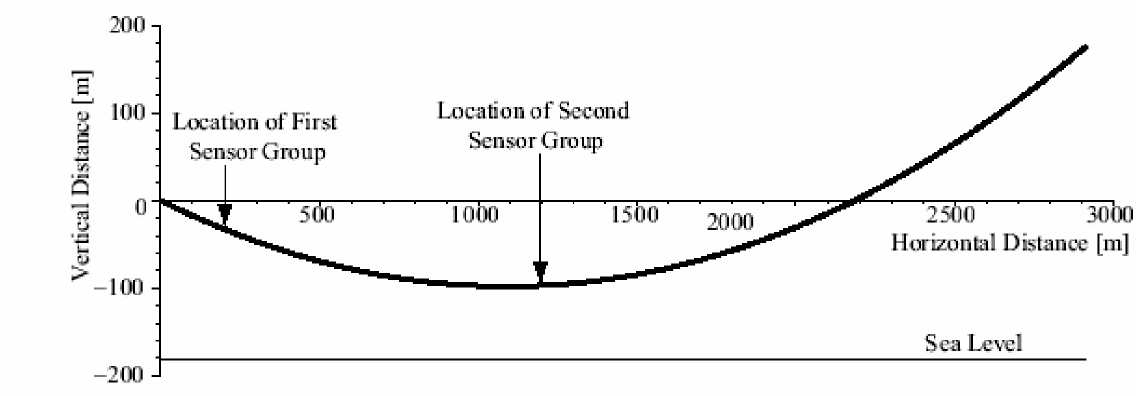

Figure 1. Overview of the Glomfjord span, with the sensor locations indicated.

Each Bragg grating sensor was placed in a slot cut in a 10 cm long aluminium strand. This aluminium strand was preformed to fit the helix of the line, and during installation this strand, complete with sensor and fibre-optic cable, was glued to one strand of the conductor. The sensors were installed in two locations with three sensors at each location, and with a distance between the individual sensors of 2 m. These locations were 200 m and 1200 m from the lower end of the span, respectively, see Figure 1. Each location was addressed with separate fibre-optic cables. The fibre cables were wrapped along the line with a spinning machine used for telecommunication cables. The installation was performed using a wagon pulled along the conductor and done in parallel with other maintenance work and installation of the new dampers along the line. The cables were terminated in a specially designed top fitting attached at the end of the conductor section. This unit combines the functions of conductor clamp, splice enclosure and corona shield. A separate cable with a fibre-optic insulator with creepage extenders was spliced to the cables along the conductor and taken down to ground along the tower. The splicing was performed at the ground and excess fibre cable was coiled in a purpose made housing that was attached close by the top fitting. Figure 2 shows some pictures from the installation. The instrumentation and a local PC were installed in a shed with temperature regulation close to the tower with available power supply.

Figure 2. Left: Picture of the Glomfjord span. Right: Termination of fibre-optic cable with creepage extenders to ground potential.

The available instrumentation was an in-house built unit [2] based on a fast tuneable laser and controlled by LabView software. It was hampered by occasional random errors which sometimes resulting in distorted time series. Because of these limitations in the available measurement equipment, the determination of absolute vibration amplitudes was somewhat unreliable and should be considered as rough estimates. The measurement procedure was a slight modification of the recommendation from [1]. The sampling frequency was 100 Hz, and the number of points in each recording was 8500, giving time series 85 seconds long. Four series were recorded each hour, with the sensors at the two locations sampled sequentially. The measurements were stored locally, and later retrieved for analyses. Meteorological data was obtained from a weather station located approximately 2 km from the span. The weather station recorded wind and temperature at each hour. Due to the distance between the span and the weather station, differences in the wind speeds at the span location and the weather station should be expected. However, the data from the weather station on wind speed are assumed to give reasonable indication of the wind speed the span is subjected to.

4. Results

Continuous recordings (four times an hour) were performed during the period from november 2002 until may 2003. The time series were spectrally analysed in order to find the vibration frequencies. The vibration amplitudes were estimated from (3) with a least squares fit of the response of the three sensors in each group. The exact distances between the sensors within each group were measured during the installation while the distance of the first sensor in each group is known approximately. The frequency of the fundamental mode was calculated from the available span data. In addition it could also be found from a least squares fit to several observed vibration frequencies in the 3-5 Hz range with a good correspondence. Hence, the variables n and x_1 (the distance to the first sensor in each group) are varied between uncertainty limits in the calculation of vibration amplitudes. A vibration spectrum example is shown in Figure 3 for the sensors located 1200 m from the tower. There are three distinct vibration events at 3.56, 3.78 and 4.11 Hz. The corresponding peak to peak vibration amplitudes were found to be 11.4, 7.6 and 4.4 mm with an estimated uncertainty of about 10%.

An analysis of all vibration events like the one given in the example above was performed for both sensor locations. In the test period more than 28000 vibration events were recorded. For the location 1200 m from the tower the weakest vibrations were buried in noise owing to a bad fibre-optic splice resulting in a noisier signal. At this location only the strongest vibrations were detected and amounted to more than 10000. Figure 4 shows a three-dimensional graph of the distribution of vibration events in terms of frequency and peak to peak vibration amplitude. The vibration amplitudes are taken as averages over the 85 second time series.

A similar distribution was found at the other location (200 m from the tower), but the amplitudes were lower (about 40-50% of the levels shown in Figure 4). This is in qualitative agreement with visual observations from the line owner who has seen the strongest vibrations at the bottom of the span. However, owing to the limitations in the measurement unit the absolute vibration amplitudes are considered to be rough estimates.

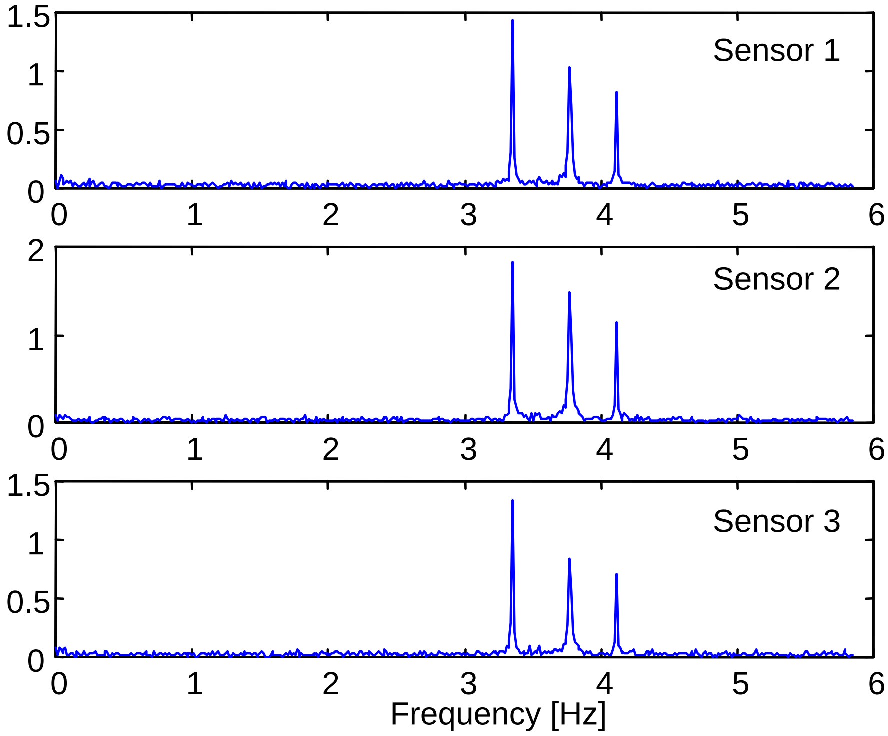

Figure 3. Example of frequency spectra from the three sensors located 1200 m from the tower. Vertical axis: Fourier transform of sensor read-out signal.

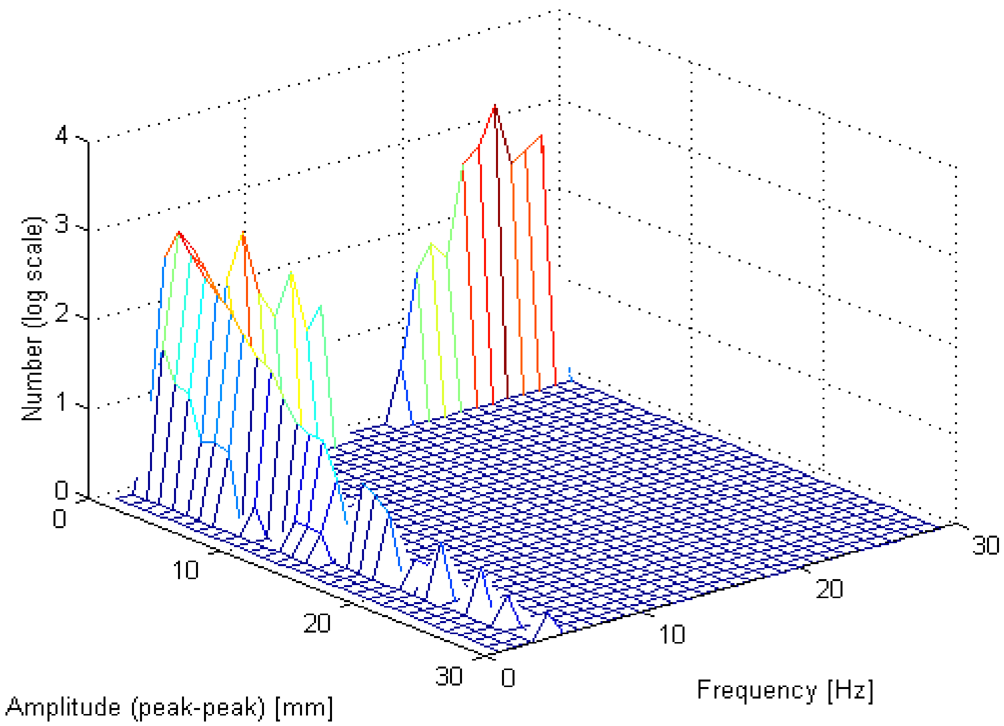

Figure 4. Distribution of vibration events at the bottom of the span.

From the results of Figure 4 it can be observed that the major vibrations occur in certain frequency bands. The strongest vibrations were found in the 3-5 Hz frequency range with maximum peak to peak amplitude close to 30 mm. In addition there were some contributions in the 7-10 Hz range with low amplitudes and many vibration events around 25 Hz. For the latter the peak to peak amplitudes were small and less than 0.5 mm. In the 14-20 Hz range the vibrations were almost absent. This particular behaviour must be attributed to the damping system which seems to be very effective in certain frequency bands and less effective in other bands like the 3-5 Hz range. The highest recorded vibration frequencies were about 30 Hz in the test period. A closer study of monthly variations was also performed and revealed no significant changes from month to month. In other words the vibration behaviour was fairly constant during the test period covering late autumn, winter and spring. The air temperature measured at the weather station close by varied from -13.9 ºC to +13.8 ºC in the test period.

The frequencies of aeolian vibrations are approximately given by the Strouhal relationship [5], which states that the frequency of vortex shedding, and hence the vibration frequency of the conductor, is proportional to the wind speed and inversely proportional to the diameter of the conductor. For the Glomfjord span a wind speed of 1 m/s corresponds to a vibration frequency of 3.5 Hz. Measurements from the nearby weather station revealed that the dominant wind velocities were in the range 0-2 m/s. The frequently observed vibrations in the range 3 to 5 Hz for wind speeds around 1-2 m/s are as expected from the Strouhal relation.

On the other hand the vibration frequencies in the range 23 to 27 Hz, occurring at a wide range of wind speeds do not follow this relationship clearly. The reason for this is not clear, but the wind is measured at a different location, in a different height above the ground. This could mean that the wind at any given place in the span can be different from the measured wind speed. However, more important is probably the effect of the dampers. The frequency characteristics of the span including the dampers, is not available, but the occurrence of frequencies in the 23-27 Hz range may indicate that the damping is less efficient at these frequencies. A closer investigation on how vibration levels and frequency varied with the wind is presented in [6].

The resolution of this measurement technique is determined by the noise level. The noise level of the measurement system was determined in periods with low or no wind yielding a sensor response with no oscillations. All sensors closest to the anchoring tower had a noise floor for the measured strain in the range $2 \cdot 10^{-7}$- $4 \cdot 10^{-7}$, whereas for the sensors in the mid-span the noise floor was found to be significantly higher, in the range of $2 \cdot 10^{-6}$- $4 \cdot 10^{-6}$ which is due to a poor fibre splice resulting in a lower signal to noise ratio. By inserting the relevant values into (3) an estimate of how large vibration amplitudes this noise corresponds to can be found. This indicates the possibility of detecting vibrations with amplitudes larger than 0.1 mm at 10 Hz, and larger than 0.02 mm at 25 Hz for the sensors nearest the anchoring tower. For the sensors in the mid-span the corresponding values are 1 mm at 10 Hz, and 0.2 mm at 25 Hz. These values represent a best case that is with a sensor located in the optimum location at an anti-node.

5. Conclusions

A new measurement method based on fibre-optic Bragg grating sensors for characterizing aeolian vibrations on overhead conductors has been demonstrated. The installed measurement system has proved its ability to detect vibrations in-span in a long overhead transmission line fjord crossing. The method offers several advantages like no need for power supply at the sensor locations, small size and mass and no influence of the high voltage environment. All parts of the system were working with no failures for the entire duration of the measurements. The vibration history of the conductor in a 6 month period was mapped. The largest vibrations were detected at the bottom of the span with maximum peak to peak amplitudes less than 30 mm in the 3-5 Hz range. Although a great number of vibration events were detected, the majority of them were weak and from the estimated vibration amplitudes it is unlikely that fatigue damage will occur.

In general vibration data obtained with this method can be used to optimize vibration damper arrangements or verify existing damper performance. Accumulated vibration data can furthermore provide information of the mechanical condition of the conductor and its remaining lifetime. In addition the method can also be used to detect other environmental loads like galloping and ice accretion in remote areas. Since FBG sensors are also temperature sensitive they are also promising for temperature monitoring of conductors.

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