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Self-sufficient vibration sensor for high voltage lines

Autonomer Vibrationssensor für Hochspannungsleitungen

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Zusammenfassung: Winde und Luftströmungen stellen eine potentielle Bedrohung für Hochspannungsleitungen dar. Die Luftbewegungen lassen die Leiterseile in beliebige Richtungen schwingen und verursachen mechanischen Stress an den Aufhängepunkten und den Leiterseilen. Um die Amplitude der Seilauslenkung zu messen, kann ein Vibrationssensor, basierend auf einer Beschleunigungsmessung, an der Leitung angebracht werden. Damit der Sensor in einem solchen Umfeld korrekt arbeitet und die Auswertung der Seilauslenkung ordnungsgemäß erfolgt, müssen zuerst Überlegungen angestellt werden. In diesem Beitrag sind diese herausgestrichen und in einen Laborprototypen eingeflossen, welcher anhand von Laborexperimenten verifiziert und charakterisiert wurde. Die Leistungsaufnahme des Prototyps sowie dessen Messunsicherheit und der mittlere quadratische Fehler, bezogen auf die Auslenkung, werden präsentiert.

Schlüsselwörter: Vibrationsmessung, Hochspannungsleitung, Spektrale Analyse, Sensorsimulation, Unsicherheitsanalyse.

Abstract: Winds and air circulations can be a potential hazard for high voltage lines. They cause the lines to move, resulting in mechanical stress at the suspension point and wear of the line itself. To estimate the stress, it is important to monitor the movements of the line. An acceleration based vibration sensor is a possible approach to measure the displacement spectrum of the line. Therefore the sensor has to work self-sufficiently on the overhead line. In this environment, design considerations are necessary with regard to a properly functioning sensor. In this paper, the most important design considerations are pointed out and a lab prototype of a vibration sensing system is set up and verified. It is characterized by means of its power

consumption and the evaluation of its uncertainty and mean squared error regarding the displacement.

Keywords: Vibration sensing, high voltage line, spectral analysis, sensor simulation, uncertainty analysis.

1 Introduction

High voltage transmission lines are an important part of the critical energy infrastructure. They transfer and distribute the electrical energy properly over wide distances throughout entire countries [1]. Thereby the towers and the overhead lines have to withstand different atmospheric weather conditions. Beside snow and icing events [2, 3] in cold climatic regions, one of the most common threats are winds and air circulations [4, 5]. Winds and air circulations excite aeolian vibrations, subspan oscillations or galloping of high voltage lines. [6, 7].

Fig. 1: a) Wind induced movements cause mechanical stress at the suspension point. b) Self-sufficient vibration sensing system to monitor movements of the line.

These movements of the lines cause wear over time [8]. Figure 1 a) illustrates wind induced movements of the line. The line can move in a random direction and cause mechanical stress at the suspension point. Beside this, the line itself wears out. To estimate the stress acting on the suspension points and the line, it is necessary to

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monitor the vibrations of the line [9]. The amplitude of the vibrations and its frequencies are of interest. Both information can be combined and displayed in the displacement spectrum. So called vibration recorders are able to measure the displacement using a position sensor [10]. Hereby, they are mounted directly at the suspension points. The exact alignment to the line and the positioning of the vibration recorders is challenging and result in a high installation effort.

A different method to obtain the displacement spectrum is an indirect approach. An acceleration based vibration sensor, is mounted on the high voltage line to monitor the movements of the line [11]. The steps to obtain the displacement spectrum from the acceleration sensor is depicted in Figure 2. The acceleration data is in

Fig. 2: General processing steps to obtain the displacement spectrum from the acceleration data.

a first step integrated twice in time domain. In the second step, the intermediate data undergoes a spectral analysis. The result of the spectral analysis is referred to as the displacement spectrum [12, 13].

Figure 1 b) illustrates a vibration sensor mounted directly on the line. Hereby, the sensor has to work self-sufficiently. A harvesting principle is required to provide the energy for the vibration sensor and the wireless communication interface. In this regard the available power for processing and transmitting of the displacement spectrum is limited. Another point that needs to be addressed is the correct processing of the measured acceleration data with respect to the spacial orientation of the sensor.

In this paper a design of a vibration sensing system for monitoring the movements of a high voltage line is presented. The system considerations for a sensor working in an environment, as depicted in Figure 1 b), are pointed out. Furthermore, an energy efficient algorithm approach for processing the displacement spectrum is presented. A sensor prototype is set up in the lab and its functionality is verified. The lab prototype is finally characterized by means of its power consumption, an uncertainty analysis [14] and an evaluation of the mean squared error regarding the displacement amplitude.

2 Design considerations

In this section, the design considerations for a self-sufficient sensor, working on a high voltage line, are pointed out. The available power for the sensor and the processing of the displacement spectrum are addressed.

2.1 Power limitations

As the vibration sensor should work self-sufficiently, it has to supply itself properly by means of a suitable energy harvesting principle. The harvester should not influence the measurement and must therefore be small and of low weight. Subsequently only a limited amount of power is available for the sensing system. The on-board system components, including an acceleration sensor and a processing unit, have to function with very little power. A further point to consider is the wireless communication interface. The processed displacement spectrum has to be transmitted to a base station where it is used to evaluate the mechanical stress. Hence, also the power consumption of the wireless interface has to be considered. A further limitation is the low amount of storage and computational power for processing the displacement spectrum. In this regard, a power efficient algorithm is needed to process the acceleration data.

2.2 Accelerometer and orientation

As shown in Figure 2, the displacement spectrum is based on the measurement of the acceleration. The sensor measures the acceleration in all three spacial dimensions. The gravity of the earth is thereby always measured as well, which leads to a high DC component of the acceleration signals. Due to this DC component, the double integrated acceleration signals show a drift. This drift of the signals leads to an undesirable result of the spectral analysis. Furthermore, the result should be independent from the sensor orientation. This would allow an easier installation of the sensor on the transmission line. The following algorithm includes the described considerations.

2.3 Algorithm for displacement evaluation

The following algorithm approach, as depicted in Figure 3, is proposed to obtain the displacement spectrum Y from the acceleration sensor. The time signals a_i of all three dimensions are measured by the acceleration sensor. In

Fig. 6: Acceleration spectrum in each dimension. Fundamental frequency is seen at 5 Hz in the z -dimension. Harmonics also arise at 10 Hz and 15 Hz. Small accelerations in the x and y -dimension occur as well.

Also the first and second harmonics can be seen. If the

Fig. 7: Comparison of displacement spectrum between lab prototype and reference. The peaks of the sensor system are broader due to the limited computational and storage resources. In terms of the displacement amplitude, the sensor system shows good agreement with the reference spectra.

spectrum of the sensor system is compared to the references, the sensing system shows good agreement with the reference spectra in terms of the displacement amplitude. Not only the main peak, but also the displacement amplitude at higher frequencies match the result of the references well. However, the sensor system clearly shows broader peaks. This is due to the limited resources in terms of storage, FFT-length and computational power of the system. Hence, the frequency resolution of the sensing system is smaller.

4 Characterization of the prototype

In this section the lab prototype is characterized by means of its power consumption and its measurement uncertainty regarding the displacement amplitude. Additionally, an error analysis for the measured displacement spectrum is presented.

4.1 Power consumption

In order to characterize the prototype in terms of its power consumption, first the different operating modes of the system are shortly introduced:

- Standby: System is idle and waits for a command to receive from the base station.
- Measurement: System measures the acceleration in all three dimensions.
- Processing: System processes the displacement spectrum.
- Transmit: Processing unit sends displacement spectrum to base station.

The average power consumption of the system for an exemplary cycle, including the described operating modes, can be seen in Figure 8. In the first phase the system is

Fig. 8: Average power consumption of sensor system during different operating modes.

in standby. The power amounts to 22 mW. After 10 s, a measurement is triggered. The power slightly increases as the 3-axis acceleration sensor starts to get active. After the measurement mode, the data is processed. A significant jump of the power up to 38 mW can be observed. The execution of the FFT requires a high amount of power for a short period of time. Once the spectrum is processed, it

is transmitted towards the base station. Also the wireless interface has to be considered in the design, as the power during transmission is about 25 % higher than in standby. After the transmission, the system returns into the standby mode. The required power of the prototype is generally low. An energy harvester that uses the magnetic field of the line can provide this power [16].

4.2 Uncertainty analysis and mean squared error

For the characterization of the lab prototype, the measurement uncertainty regarding the displacement amplitude and the mean squared error of the displacement are presented. To obtain the uncertainty of the displacement, a model of the sensor system is set up and a Monte Carlo (MC) simulation is performed. The result of the MC simulation is depicted in Figure 9. As can be seen, the standard deviation of the displacement depends on the signal frequency. For an increasing signal frequency, the standard deviation of the displacement decreases quadratically.

Fig. 9: Result of Monte Carlo Simulation and CRLB. The standard deviation of the displacement depends quadratically on the signal frequency.

To assess the result of the MC simulation, it is compared to the Cramér-Rao lower bound (CRLB). The CRLB is the theoretically lowest possible standard deviation of the displacement that can be achieved. For the computation of the CRLB it is assumed that the sensing system is ideally excited in only one dimension. Hence, it is sufficient to analyse the displacement uncertainty only in this dimension. Following these assumptions, the CRLB can be computed numerically, given a displacement of the form

$$y[n] = Y \sin(2\pi f T_s n + \varphi). \quad (1)$$

Here, f denotes the signal frequency, Y denotes the displacement amplitude, and T_s is the sampling period, n labels the sample index and φ represents the phase of the signal. For the displacement of Equation (1), the acceleration signal model

$$s[n] = -4\pi^2 f^2 Y \sin(2\pi f T_s n + \varphi) \quad (2)$$

for a single dimension is derived. According to [17], the variance of the displacement Y is given as

$$\text{var}(Y) \geq \frac{\sigma_a^2}{\sum_{n=0}^{N-1} \left(\frac{\partial s[n]}{\partial Y} \right)^2}, \quad (3)$$

where σ_a is the measurement uncertainty of the acceleration sensor and N is the number of total samples. Given the signal model of Equation (2) and the relation of Equation (3), the CRLB for the displacement can be computed. The result of the CRLB is depicted in Figure 9. It confirms the quadratic dependency between the standard deviation of the displacement and the signal frequency. Although the MC simulation of the sensor system considers all three dimensions, the result is close to the CRLB.

Finally, the mean squared error (MSE) for the displacement is computed. The result of the square root of the MSE is pictured in Figure 10. Hereby, the im-

Fig. 10: $\sqrt{\text{MSE}}$ of the displacement when using different window functions. At some specific frequencies, the rectangle window gives a lower error, but overall the Flattop window performs better for the given frequency range.

portance of the used window function is presented. The window weights the acceleration signals before they are transformed into the frequency domain. As the correct displacement amplitude is of importance, a Flattop window is used. Its characteristic property is the correct representation of the signal amplitude in the frequency domain. For comparison, a further simulation result, using a rectangular window is also shown. At some specific signal

frequencies, the rectangle window performs better than the flattop window. However, this is only the case if coherent sampling occurs, which rarely happens. Overall the flattop window performs better than the rectangle window. The result of the error analysis shows that the precision of the displacement is in the area of μm over the frequency range.

5 Conclusion

In this paper the design of a self-sufficient vibration sensor for monitoring oscillations and vibrations of a high voltage line is presented. The design considerations regarding a sensor working self-sufficiently on an overhead line are pointed out. An algorithm approach for evaluating the displacement spectrum, is proposed and implemented. A lab prototype is set up and its measured displacement spectrum is verified by different reference measurements. A characterization of the lab prototype is archived by presenting its power consumption for different operating modes and by the comparison of a MC simulation with the CRLB. The final evaluation of the mean squared error shows the importance of the window function and that the precision of the measured displacement is within the range of μm .

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