Comparison of Fatigue Lifetime Estimation of a Conductor Based on a Standard Vibration Device and Other Structural Health Monitoring System Sensors

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Abstract This article presents an experimental work developed in the context of the study of conductors' fatigue due to the turbulent effect of wind on an overhead high-voltage transmission line. The research is centred on the laboratory study of a conductor segment with a 17 m length. The cable model, fitted with typical anchorages adopted in transmission lines, is mounted on a specially designed anchoring system following the normative prescriptions of CIGRÉ. An extensive monitoring system is installed, including a load cell, several accelerometers, LVDTs and fibre optic sensors to assess the conductor's dynamic properties and the corresponding dynamic response to the wind loads, here simulated by a random excitation applied from a shaker. Based on the conductor response measured with the different sensors, with and without a Stockbridge damper, the fatigue lifetime of the conductor is calculated. A comparison is made of the fatigue lifetime estimated from acceleration, strain or LVDT measurements, the latter simulating the procedure typically used based on the VIBREC measurements. Finally, the Stockbridge damper's dissipation capacity in increasing the conductivity lifetime subject to aeolian vibrations is analysed as a function of the position of the damper.

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1   Fatigue of Conductors

In overhead high-voltage transmission lines, maintenance is essential to increase the lifetime of the conductors and save electricity distributor companies' investments. However, these structures are prone to one of the most complicated mechanical problems related to damage and failure: fretting fatigue. Fretting results from relative motion between the internal conductor wires and their contact with clamps and dampers. This phenomenon is mainly caused by aeolian vibrations, also known as vortex-shedding resonance. These vibrations are caused by the development of alternate vortices at the top and bottom of the conductor, which induce a vertical cable movement that results in bending at the anchorage point near the tower for specific wind velocities. Combining bending and tension loads at the cable could lead to wire fatigue.

Aeolian vibrations in cable conductors occur at low wind velocities between 0.5 and 7 m/s, at a frequency range between 3 and 120 Hz, with amplitudes ranging from 0.01 to 1 diameter [1].

2   S–N Curves and CIGRÉ's Safe Border Line (CSBL)

The fatigue performance of a material is often characterised by utilising the stress-life approach and S–N curves, which plot the cyclic stress (S) vs the number of cycles until failure (N) during a laboratory test. The conditions for stopping the test are either the failure of 10 per cent of the cable's wires or of the three outer layer wires. Due to the problematic execution and high costs associated with this type of test, the International Council for Large Electric Systems (CIGRÉ) developed a Safe Border Line curve (CSBL) to assist in determining the lifetime of conductors from a simplified method. The following equation expresses the Safe Border Line curve

$$\sigma_a = A \cdot N_i^B \tag{1}$$

The constants A and B are related to the number of fatigue cycles N_i for a specified level of stress and the number of aluminium wire layers in a conductor. The stress amplitude is denoted by the symbol σ_a and is measured in MPa. According to [1], the values of these parameters are shown in Table 1.

Table 1 Constant values A and B for the CSBL curve

# of layers	$N < 2 \times 10^7$		$N > 2 \times 10^7$	
	A	B	A	B
1	730	−0.2	430	−0.17
>1	450	−0.2	263	−0.17

2.1 Poffenberger and Swart Equation

The precise evaluation of stress and strain on conductors is a challenging undertaking. Poffenberger and Swart [2] found a direct correlation between the dynamic bending stress (σ_{PS}) at the wires' outer layer and the peak-to-peak vibration amplitude (Y_b) via an analytical formulation. The Poffenberger-Swart equation is as follows

$$\sigma_{PS} = K \cdot Y_b \tag{2}$$

The constant K in this equation converts the vertical amplitude measured at 89 mm from the last point of contact (LPC) into bending stress (0-to-peak).

In this study, the bending amplitude of vibration Y_b is calculated using different procedures to compare the results of a standard vibration device (VIBREC) with the structural health monitoring calculations using accelerometers and fibre optical sensors. The VIBREC is simulated here using a linear variable differential transformer (LVDT).

3 Stockbridge Dampers

To mitigate aeolian vibrations on conductors of overhead high-voltage transmission lines, the correct position of the Stockbridge damper is crucial. The damper position is associated with its capacity to dissipate wind-induced energy in the structural system. Installing the Stockbridge dampers in improper locations might increase mechanical overload on the cable, resulting in a shorter lifetime.

The Stockbridge generally consists of two rigid masses connected to both ends of a messenger cable. A rigid clamp ensures the connection between the conductor and the damper, which allows displacement transmission from the conductor to the Stockbridge. The vibration of the inertial masses connected to the messenger cable induces bending, which dissipates energy through the friction caused by the relative movement of the cable's internal wires. Maximum levels of energy dissipation occur in a frequency band close to their natural frequency when the Stockbridge is excited at that frequency [3]. If the conductor and Stockbridge damper dissipate more energy than that imparted by the wind, the conductor will vibrate with less amplitude and for a shorter period.

To guarantee the system efficiency, CIGRE recommends that the Stockbridge damper should be placed at a distance of 0.85λ/2 from the last point of contact, as shown in Fig. 1, where λ is the wavelength of the highest mode to be mitigated, and can be expressed as follows

$$\lambda = \frac{1}{f_n} \cdot \sqrt{\frac{T}{m}} \tag{3}$$

Fig. 1 CIGRE's recommended distance of the Stockbridge installation from the cable clamp
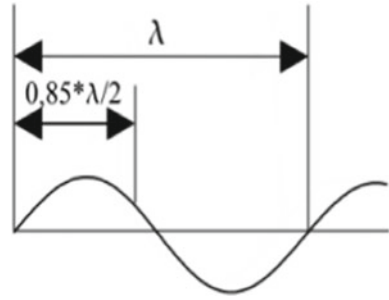
In Eq. (5), f_n is the cable's natural frequency in *Hz*, *T* is the tension force, expressed in *N*, and *m* is cable mass per unit of length, expressed in *kg/m*.

Resonance occurs when the frequency of wind excitation (Strouhal frequency) approaches the natural frequency of the conductor. The expression for the critical wind frequency can be derived from the Strouhal number of 0.185, which is the recommended number for the specific case of cables in overhead high-voltage transmission lines.

$$f_n = \frac{0.185 \cdot U}{d} \tag{4}$$

where *U* is the wind velocity in *m/s*, and *d* is the diameter of the conductor, expressed in *m*.

4 VIBREC500 Vibration Recorder

VIBREC (Fig. 2) is the most widely used device for measuring aeolian vibrations. The device records peak-to-peak relative vibration amplitudes between two sections and has an autonomy of approximately one year, depending on the ambient temperature and the acquisition time interval.

VIBREC does not continually record data due to the need to manage the battery life and memory. The standard acquisition consists of saving 10 s of active-time data within 15 min of an inactive interval, per CIGRÉ's recommendation, establishing a minimum monitoring duration of three months.

This standard device is capable of calculating the remaining lifetime of the conductor. The equipment analysis follows the most recent CIGRÉ [4] and IEEE [5] standards. The data are expressed through an S–N curve relating each block of stress to the number of cycles, and the damage at the conductor is determined using the Miner's rule using the expression

$$D = \sum_{i=1}^{m} \frac{n_i}{N_{fi}} \tag{5}$$

and the procedure shown in Fig. 3. The S–N curve obtained with the recorded data is compared with the CIGRÉ's Safe Border Line [1], bringing the final damage value, which is extrapolated to a one-year period.

Finally, the lifetime is given by the following equation

$$V = \frac{1}{D} \tag{6}$$

where D is the accumulated damage, and V is the lifetime in *years*.

As stated before, the VIBREC device was simulated in this study using a pair of LVDT sensors to measure the relative vibrations at two sections, recording peak-to-peak amplitudes.
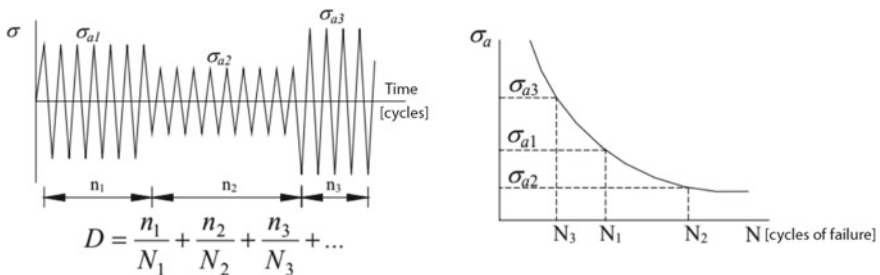
Fig. 3 Damage calculation procedure

5   Laboratory Setup

A setup was created to accommodate the conductor and the anchoring systems within the space of the FEUP laboratory to conduct the tests correctly and replicate the conductor's behaviour on site (Fig. 4).

The setup comprises the conductor, which is roughly 17 m in length, and two steel-plate anchoring modules. For this experiment, the maximum tension at the supports is 23,3kN, which is 20% of the conductor's RTS.

The analysed conductor is a BEAR-325 type ACSR (Aluminum Conductor Steel Reinforced) cable with 30 aluminium wires, seven steel wires in the reinforcement core, and an external diameter of 23 mm.

5.1   Instrumentation

To realise the fatigue experiments and find the best position of the Stockbridge to mitigate aeolian vibrations, a group of sensors was installed along the conductor. As cable tension control is essential in this kind of dynamic experiment, a force transducer is positioned at the active anchorage point to measure the tension force applied to the conductor by a jack. Three piezoelectric accelerometers were used in the experiments to characterise the structural response of the conductor subjected to forced vibrations: one was installed near the anchorage point to permit the calculation of the bending amplitude of vibration using a double integration procedure to transform accelerations into displacements. To simulate the VIBREC device behaviour, a pair of LVDTs were installed at the end of the cable (Fig. 4). The first sensor was

Fig. 4 Setup and instrumentation prepared for tests at the conductor

placed 42 mm from the LPC and the second sensor 89 mm from the other. Figure 5 shows the scheme of installation.

Finally, a group of fibre optical sensors were installed on the conductor better to understand the conductor's behaviour at low frequencies. The sensors were previously tested and calibrated before the tests. They were installed in the section closest to the position chosen for the Stockbridge (72 cm from the last point of contact LPC), near the end anchorage point. Figure 6 shows the applied setup, which consists of a fibreglass sleeve with a "1/4 cane" shape and an interior diameter equal to the conductor's diameter incorporating three FBG optical transducers. Two are strain gauges arranged longitudinally at the ends of the sleeve, and the other is a temperature transducer insulated from strain located in the middle zone.
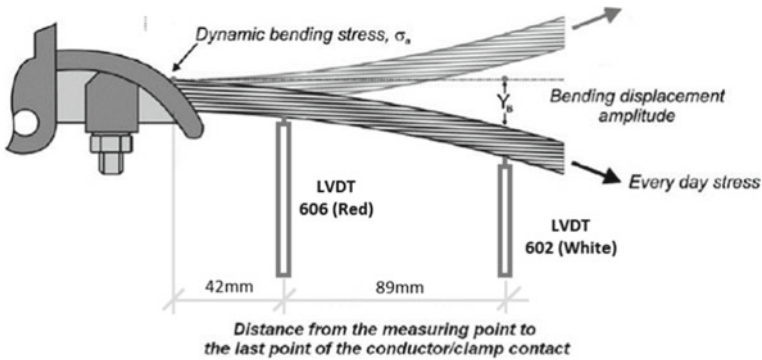

Fig. 5 LVDTs position relative to the Last Point of Contact (LPC)

Fig. 6 Fiber optical sensors installed on the conductor

6   Best Stockbridge Position Along the Cable

6.1   Tests Description

To determine the best position of the Stockbridge damper that minimises the vibration amplitudes and, consequently, the bending stresses at the anchorages, four tests were carried out using a shaker to simulate the wind-induced action. The tests consisted of 1 h measurement of the conductor response under excitation close to the midspan with a random force. This force was generated with a frequency content defined from 3 to 80 Hz to simulate Aeolian vibrations. A first test was carried out without the presence of the damper, and the other three were conducted with the Stockbridge installed at three different positions. The position recommended by CIGRE was defined considering the maximum wind speed that produces wind vibrations, which is 7 m/s. Using Eq. (6), it is possible to determine the vortex-shedding frequency associated with such wind speed for a Strouhal number of 0.185

$$f_n = \frac{0.185 \cdot U}{d} = \frac{0.185 \cdot 7\,\text{m/s}}{0.023\,\text{m}} = 56\,\text{Hz}$$

The Stockbridge frequency range recommended in the literature is between 0.7 and $1.3\,f_n$, where f_n is the previously calculated maximum. In this way, the range of frequencies where the damper will act is from 42 to 80 Hz, approximately. In addition, as wind-induced vibrations occur more frequently at low speeds, a frequency referring to the wind speed of 3 m/s was also added, corresponding to a frequency of 24 Hz. Table 2 presents the calculation parameters used in the tests.

As a result of the tests, it is possible to determine the bending amplitude of vibrations according to the Stockbridge positions. The position which leads to a minimum amplitude of vibration is considered the best position to install the damper, which means that at this position, the Stockbridge dissipates more energy. Figure 7 shows the amplitudes calculated using different sensors, which are also systematised in Table 3. "Acc" is the accelerometer, and "FBG" is the fibre optical sensor.

It is possible to observe that the minimum amplitudes are reached when the damper is installed at 72 cm from the last contact point, as recommended by CIGRE. Position 0 indicates the test without the presence of the damper.

Table 2 Parameters for Stockbridge best position tests

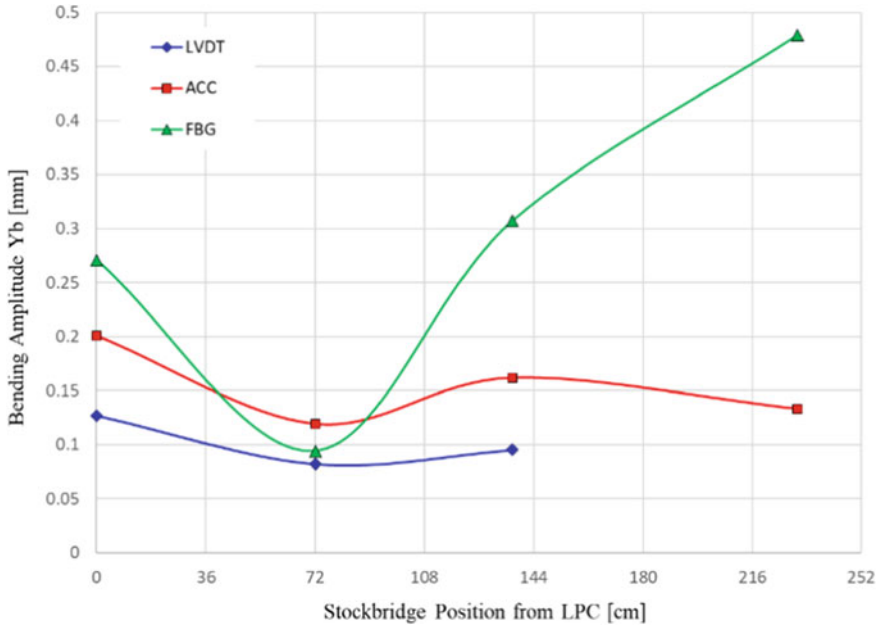| Wind velocity [m/s]	Strouhal frequency [Hz]	Wavelength λ [m]	Stockbridge Pos. [m]
3.0	24.0	5.77	2.31
5.2	42.0	3.29	1.37
10.0	80.0	1.73	0.72 (CIGRE)

Fig. 7 Bending amplitude of vibration according to the Stockbridge position

**Table 3** Amplitudes of vibration Y_b according to the Stockbridge position

Stockbridge Pos. [cm]	LVDT—Y_b [mm]	ACC—Y_b [mm]	FBG—Y_b [mm]
Without damper	0.127	0.201	0.271
72.0 (CIGRE)	**0.082**	**0.119**	**0.094**
137.0	0.095	0.162	0.307
231.0	–	0.133	0.479

7 Lifetime Estimation

After defining the best position for the Stockbridge installation, the estimates of the lifetime due to fatigue of the conductor subjected to wind actions were calculated. Finally, the total damage was estimated using the Rainflow method for counting fatigue cycles and the procedure described in Sect. 5, simulating the calculation made by VIBREC.

Figure 8 and Table 4 present the lifetime calculation expressed in years for each type of sensor according to the position of the Stockbridge. As expected, the position that leads to the most extended lifetime is the position 72 cm from the last point of contact, which is in accordance with the proposition established by CIGRE. It is also possible to observe that all sensors present the same result for the best position of the damper, indicating that structural health monitoring using several types of sensors

is feasible and reliable compared to the standard device VIBREC. Nevertheless, it is observed that the calculations made using different sensors lead to very different fatigue life estimations, which is consistent with the different impact of the response frequency content in the different measured quantities, such as displacement, strain or acceleration.
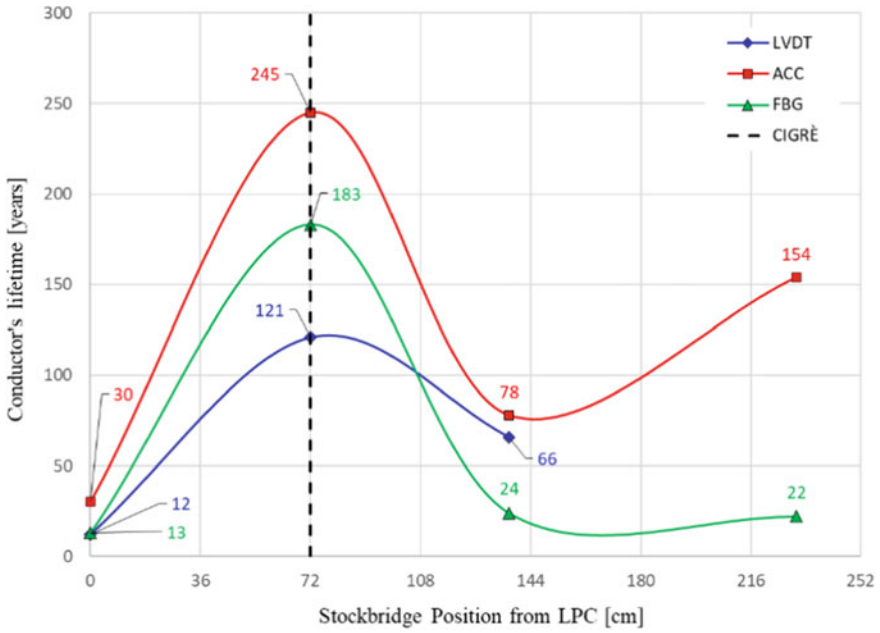
Fig. 8 Lifetime estimation according to the Stockbridge position

Table 4 Lifetime estimation calculated using different sensors

Stockbridge Pos. [cm]	LVDT—V [years]	ACC—V [years]	FBG—V [years]
Without damper	12.0	30.0	13.0
72.0 (CIGRE)	121.0	245.0	183.0
137.0	66.0	78.0	24.0
231.0	–	154.0	22.0

8 Conclusions

In overhead high-voltage transmission lines, the correct damper position is an important variable to consider in the conductor's design. In general, the manufacturers design the Stockbridge positions, and the lifetime estimations are made using standard recording devices like VIBREC. This work presented an alternative using structural health monitoring with accelerometers and fibre optical sensors positioned along the conductor. The calculations follow the CIGRE recommendation, which defines that the best position for the damper is at $0.85\lambda/2$, considering the wavelength for the highest frequency in the range of Aeolian vibrations. This study also indicates that other quantities measured with a structural health monitoring system could be used to determine the dampers' best position and calculate the conductor's estimated lifetime. Nevertheless, a calibration of the fatigue lifetime estimates is required.

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