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METROLOGICAL EVALUATION OF AN OPTICAL FIBER ACCELEROMETER FOR POWER TRANSMISSION LINES MONITORING

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Abstract: This paper describes the characteristics and metrological evaluation of an optical fiber accelerometer designed for monitoring vibrations in cables of power transmission lines. The calibration performed with laser interferometer at the Brazilian National Institute of Metrology and other tests conducted at the Electric Energy Research Center are discussed. Advantages over existing similar instruments are stressed.

Keywords: accelerometer, power line, fiber optic.

1. INTRODUCTION

Aeolian and ice induced vibrations are among the main causes of failures in power transmission lines, thus justifying the monitoring of these phenomena. However, adverse ambient conditions such as high electromagnetic fields, wide temperature operation range, and open-air installation among others, make this task difficult to be accomplished employing traditional transducer technology.

The few devices available today for vibration recording in power transmission cables present severe shortcomings limiting the quantity and quality of data measurements. Fiber optic sensors, with their electromagnetic immunity, remote sensing and multiplexing capabilities, offer an interesting alternative for measurement instruments designed for power transmission lines applications.

1.1. Vibration of power line cables

Aeolian and ice induced vibration and the resulting cable fatigue are phenomena known to electric-energy transmission engineers and researchers for more than 70 years [1]. The alternate shedding of wind-induced vortices from the top and bottom sides of the cable creates a cycling pressure unbalance, causing the cable to move up and down transversally to the direction of air flow.

The cyclic induced cable motions are usually divided in three types [2]:

a) Aeolian Vibration: caused by low speed winds (1 to 7 m/s) on single cables, resulting in low amplitude vibration in the range of 3 to 150 Hz.

b) Gallop: caused by medium speed winds (7 to 18 m/s) on cables with asymmetrical ice deposit, resulting in high amplitude vibration of very low frequency (0.08 to 3 Hz).

c) Wake-induced oscillation: caused by low-to-medium speed winds (4 to 18 m/s) on bundled cables, resulting in medium amplitude vibrations of low frequency (0.15 to 10 Hz).

While aeolian vibration and gallop result in vertical vibrations, wake-induced oscillations generate motion in three degrees of freedom (vertical, horizontal and rotational).

1.2. Vibration monitoring in power lines

Despite the knowledge about vibrations in transmission line cables, the available instruments for vibration recording in power lines still lack good data sampling, storage, and transmission capabilities, due entirely to the harsh environmental conditions to which such instruments are submitted when installed onto high voltage cables.

Due to limitations in battery life, a typical vibration recorder of this kind will work for no more than 3 months and register only around 1 % of the vibration cycles of the cable. Considering the inherent wide variation of wind direction and velocity and, consequently, of the induced vibration amplitudes and frequency, there is a consensus that none of the vibration recorders available today meet the requirements of the electric power industry [3].

This situation offers an opportunity for developing a vibration instrument with longer monitoring period, real time sampling rate, and severe environment withstanding capabilities. All these features can be obtained with fiber optic sensor technology.

1.3. Optical fiber Bragg grating (FBG) sensors

Fiber Bragg Grating (FBG) is an optical sensor technology which consists in introducing, along a small region of an optical fiber, a spatial, periodic modulation in the refractive index of the fiber core.

This modified portion of the fiber becomes a spectral filter which, when illuminated by a broadband optical signal, reflects only a narrow band of light around a center wavelength, called Bragg wavelength (λ_B), as seen in fig. 1.

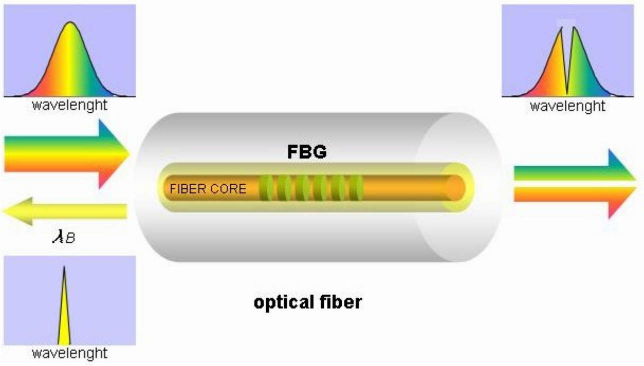

Fig. 1. Fiber Bragg Grating

This spectral filter is temperature and strain-dependent, so that monitoring the Bragg wavelength allows measuring those quantities.

Together with other fiber optical sensor technologies, FBGs offer some advantages over regular transducers, such as linearity of response over many orders of magnitude, electromagnetic interference immunity, durability against high radiation environments, low signal losses, high temperature (up to 200°C) tolerance, multiplexing capability, among others.

Compared to other optical techniques FBGs have, as main advantage, the fact that the measurand information is wavelength-encoded, rendering the sensor immune to source power and connector losses [4].

All these characteristics make FBG a very interesting technique for instruments designed to work under adverse or dynamic conditions, which is the case of power line cables vibration monitoring.

2. OPTICAL FIBER ACCELEROMETER

The accelerometer was developed from an earlier triaxial general purpose prototype [5]. For power line application, an optical accelerometer was designed based on the single-axis module showed in figure 2, where FBGs are used as spring elements at the same temperature, but subjected to opposite strains.

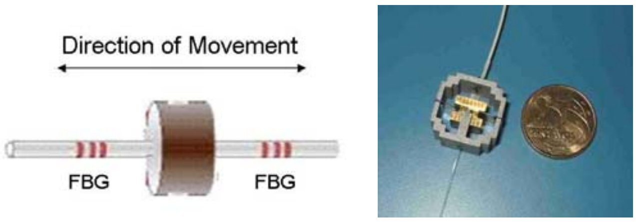

Fig. 2. Single-axis module of the accelerometer

Two single-axis modules were combined into a biaxial optical accelerometer, able to perform wake-induced oscillation measurements — a feature not available in current power line vibration recorders, which take only one-degree-of-freedom measurements.

The modules were encapsulated in a duralumin cylindrical covering, designed to be moisture and dust free. The cylindrical form was choosed to avoid corona and radio interference effects caused by high voltage. A duralumin clamp provides the attachment to the power line cable (v. figure 3).

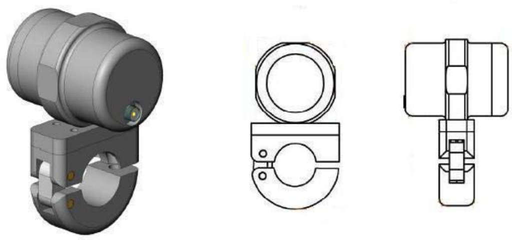

Fig. 3. Complete optical accelerometer

An in-rack mounted interrogation system, composed of CWDM optical filters, photodetectors, AD conversion board and an internal PC running a LabView based software, complete the instrument.

The optical accelerometer was designed to allow real time sampling rate and storage capacity up to one year of continuous reading, features that surpass those available in commercial devices.

To comply with the typical cable motion characteristics, the accelerometer should be able to measure frequencies in the range of 0 to 150 Hz and accelerations up to 30 m/s².

To guarantee these measurement demands and evaluate the accuracy and repeatability of the instrument being developed, a series of tests were conducted with the optical accelerometer.

3. CALIBRATION BY LASER INTERFEROMETRY

The single-axis module of the accelerometer and its interrogation system were calibrated at the Brazilian National Institute of Metrology (INMETRO). It was used an absolute calibration system based on the laser interferometric method, according to the ISO 16063-11 standard [6], with 0.5 % uncertainty in the 10 to 1,000 Hz frequency range.

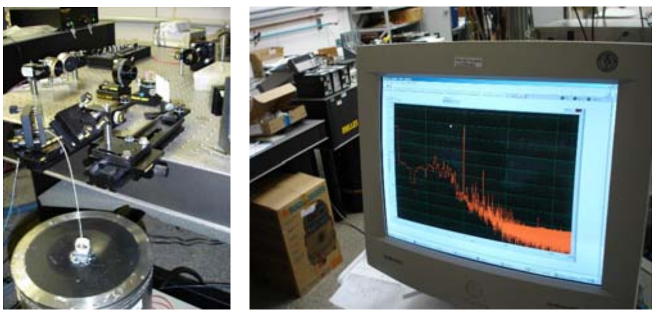

Fig. 4. Calibration setup of the single-axis module of the accelerometer

Around 500 readings were made, covering the range of 10 - 150 Hz and accelerations up to 40 m/s².

The output of the accelerometer was the logarithmic of the ratio of current signals from two photodetectors, as shown in (1):

$$Acc\,out = \log \frac{Phot_1}{Phot_2} \quad (1)$$

The adimensional wave thus obtained has a constant (DC) and an alternate (AC) component. The AC component was demonstrated [7] to have a linear relationship to the Bragg wavelength displacement, therefore to the acceleration applied to the sensor.

Nevertheless, this AC signal is not entirely independent from frequency, so a correction to this effect is necessary.

To achieve this, readings were first grouped by input frequency and inconsistent values were eliminated using Chauvenet's criteria. Then, a tendency equation was calculated by applying the least square method on the remaining data.

Taking the median of frequencies (75 Hz) as a reference, a correction equation was determined.

Then, the corrected readings were regrouped by input acceleration and again submitted to Chauvenet's criteria. The least square method was applied to the average value of each subgroup in order to determine the calibration equation.

The steps to obtain the calibration curve are showed in the flowchart of figure 5. The calibration curve itself (a straight-line) is showed in figure 6.

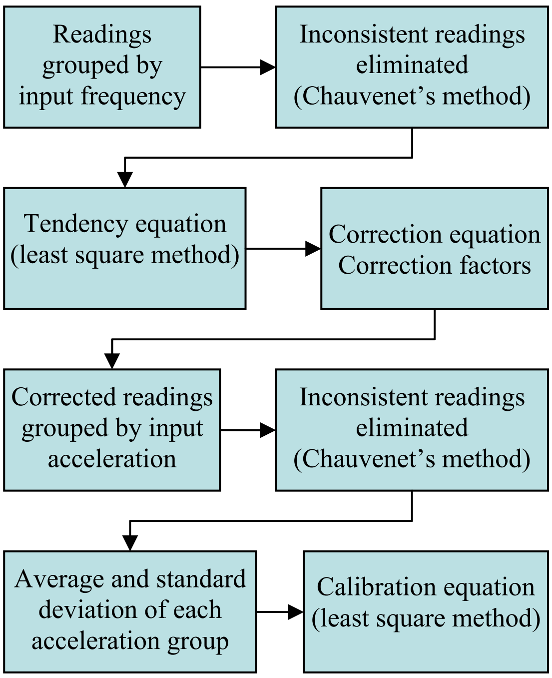

Fig. 5. Flowchart for obtaining the calibration equation

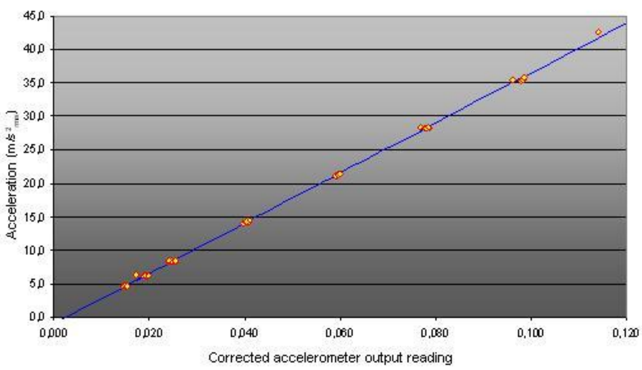

Fig. 6. Calibration curve plotted

4. UNCERTAINTY OF MEASUREMENT

The calculation of the uncertainty of measurement for the accelerometer followed the general rules proposed by the ISO-GUM [8] and was determined by equations (2) e (3):

$$u_{C\ ACEL} = \sqrt{(u_{LI})^2 + (u_{CC})^2 + \left(\frac{\partial\, acel}{\partial\, IS} u_{IS}\right)^2} \quad (2)$$

$u_{C\ ACEL}$: standard uncertainty of the accelerometer
u_{LI} : standard uncertainty of the laser interferometer
u_{CC} : standard uncertainty of the calibration curve
u_{IS} : standard uncertainty of the interrogation system
$\frac{\partial\, acel}{\partial\, IS}$: sensitivity coefficient of the calibration curve

$$U_{C\ ACEL} = 2\ u_{C\ ACEL} \quad (3)$$

$U_{C\ ACEL}$: expanded uncertainty of the accelerometer, considering a Gaussian distribution and 95.45 % level of confidence.

Table 1 presents the main values used to determine the standard uncertainties.

Table 1. Parameters for calculation of standard uncertainties

	U	Type	Distr.	Conf.	k	u
u_{LI}	± 0,5 %	A	Gauss	95.45%	2	0.0025
u_{CC}	Calibration curve average squared-deviation					0.2787
u_{IS}	± 0,5 %	B	Rect	100 %	$\sqrt{3}$	0.00408

The sensitivity coefficient of the calibration equation was calculated as 374.1943.

The resultant expanded uncertainty is 0.6 m/s², in the range of 10 to 150 Hz, for accelerations up to 40 m/s² [9].

5. TESTS ON INDOOR VIBRATING SPAN

To study the performance of the complete accelerometer on conditions close to the expected real installation, tests were conducted at an indoor vibrating span at the Electric Energy Research Center (CEPEL) facilities, in Rio the Janeiro, Brazil.

A typical transmission line cable, stretched along a 52 m span, was submitted to a transversal vibration to simulate a real power cable under aeolian excitation.

The optical accelerometer was mounted onto the cable, with a standard piezoelectric accelerometer provided as a reference, as shown in figure 7.

Fig. 7. Optical accelerometer under indoor vibrating span tests

The indoor tests intended, among other studies, to verify some metrological characteristics of the optical accelerometer, such as accuracy, drift and hysteresis.

5.1. Accuracy

The output of the optical accelerometer was compared with that of a commercial piezoelectric accelerometer (Endevco model 25B), for different sets of frequencies and accelerations imposed to the vibrating span.

Figure 8 shows a typical response, for a 12.5 Hz excitation. It can be seen that both outputs keep a close agreement.

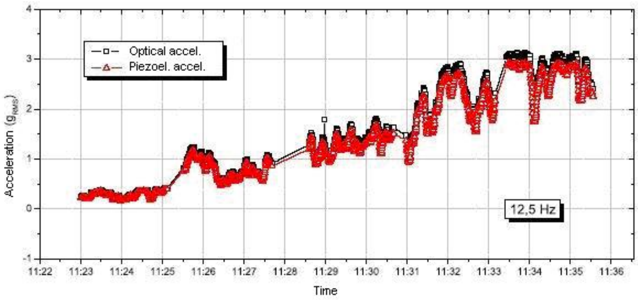

Fig. 8. Investigation of the accelerometer accuracy at 12.5 Hz

5.2. Drift

Limitations on the available laboratory time made it not viable to conduct a long drift examination.

Figure 9 shows the results of a continuous 1 hour reading of the optical and piezoelectric accelerometers, at 80 Hz.

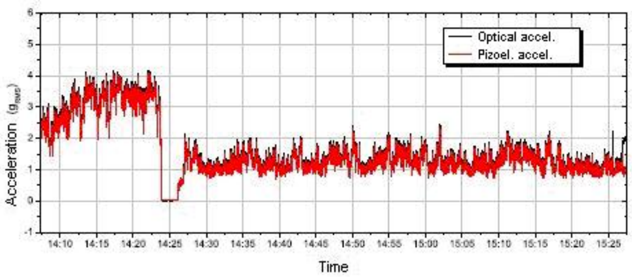

Fig. 9. Investigation of the accelerometer drift at 80 Hz

As a curiosity, it can be seen a short period of zero acceleration — correctly measured for both instruments — when the excitation system was turned off due to overheating.

The good agreement between the outputs attests the absence of drift during the test.

5.3. Histeresys

In order to check the absence of hysteresis, readings of the optical and the piezoelectric accelerometer were compared first rising, than decreasing the acceleration imposed on the cable by the shaker, keeping constant the vibration frequency.

Figure 10 presents the results obtained under 40 Hz excitation. A second set of up and down readings were taken under 16 Hz.

To mathematically evaluate the presence of hysteresis, curves were adjusted — respectively to the rising and decreasing groups of readings — using the least square method. This resulted in two generic straight-lines ($y = C_1 x + C_2$) for each frequency of excitation.

For each pair of straight-lines, the point of greatest difference ($D = \max | y_{UP} - y_{DOWN} |$) was determined.

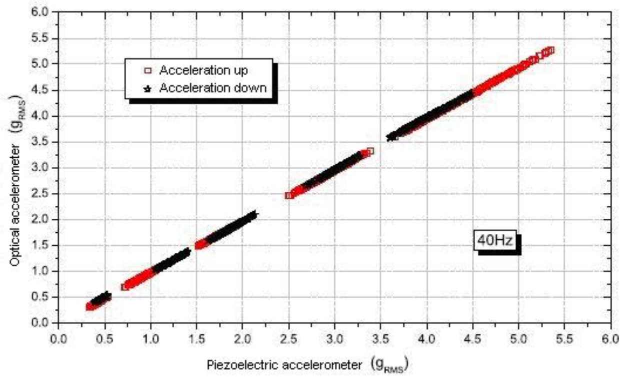

Fig. 10. Investigation of the accelerometer histeresys at 40 Hz

The average squared-deviation of each straight-line adjust was taken as its standard uncertainty (u_C).

Considering a Gaussian distribution and 95.45% level of confidence (k = 2), the expanded uncertainty is:

$$U_C = 2\, u_C \quad (4)$$

It was shown [9] that in all the cases:

$$D < U_{UP} + U_{DOWN} \quad (5)$$

This means that the hysteresis is not significant.

6. TESTS ON OUTDOOR NON-ENERGIZED SPAN

From March, 2005 to the present moment, tests have been conducted on an outdoor non-energized span situated at the Expansion's Maintenance Center at the city of Pires do Rio, in the state of Goiás (figures 11 and 12).

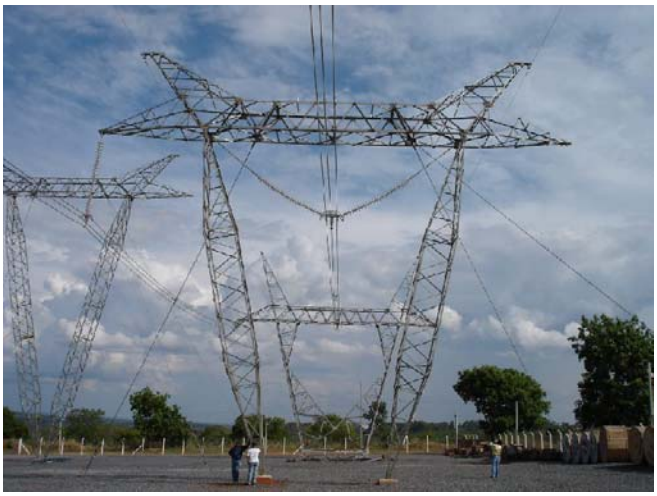

Fig. 11. Outdoor span at Expansion's Maintenance Center

Fig. 12. Installation of the optical accelerometer

These tests have been used to check the behavior of the accelerometer under ambient conditions (temperature, wind, rain, solar radiation etc.) similar to those expected in real operation.

Also, the outdoor installation was used to observe the response of the instrument to real aeolian vibrations, as well to asynchronous and impulse vibration waves, mechanically imposed on the cables.

The results have allowed studying improvements in the accelerometer design, as well as in the system interface, since the instrument is being developed to be used by power line maintenance teams.

7. FUTURE WORKS

Next steps in the research program will include laboratory high voltage tests, sensitivity analysis under high temperatures (up to 150ºC) and real power line span tests.

All these are expected to be conducted in 2006 and 2007.

8. CONCLUSION

So far, all the tests have shown that the optical accelerometer is viable for use in power lines, with advantageous features compared to existing similar devices.

The calibration instrumentation and procedure, as well as results from indoor span tests, have shown that acceleration and frequency can be measured in the intended range (0 to 40 m/s² and 0 to 150 Hz).

The expanded uncertainty of 0.6 m/s² is adequate to the goals of this instrument.

ACKNOWLEDGMENTS

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