Comparative analysis of optical-fibre interferometric sensors versus accelerometers: application to vibrations inside high-power transformers

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Abstract

We report the results of calibration of an optical-fibre (OF) probe designed for interferometric measurement of vibrations inside high-power transformers. The sensor is highly sensitive in this harsh environment of electromagnetic fields, wide temperature range and oil immersion. A comparative analysis with commercial piezoelectric accelerometers is also presented, focusing on two experiments: the common calibration with a free-space Michelson interferometer that has a controlled moving arm and calibration by obtaining the transference function of magnetostriction in the magnetic laminates by dynamic means. Both methods confirm the extremely high performance of the OF interferometric sensor and the limitations of accelerometers with characteristic low-amplitude vibrations (submicron) and a large range of measurement, as well as for a typical low frequency (100 Hz) but wide bandwidth for the harmonics. The OF probe detects the dynamic strain of deformed elements and the displacement between them. Proper design of the sensor improves its sensitivity through magnification, reaching a resolution of better than 1 nm. Finally, we demonstrate on-site measurements inside two power transformers.

Keywords: Interferometry, optical-fibre sensors, mechanical vibration measurements, dynamic strain/displacement, harsh environments, power transformers

(Some figures in this article are in colour only in the electronic version)

1. Introduction

Technological advances in optical fibre (OF) sensing deal with new applications where the intrinsic properties of the glass-based materials offer great benefits, as for example under harsh conditions of electromagnetic fields and temperature [1]. Some research has been focused on OF sensing applied to monitoring and diagnostics of electric power plants and power transmission systems. In the case of applications inside power transformers, temperature and vibration are the most interesting parameters which need to be controlled. The behaviour of transformers as they age is closely related to the temperature of the cooling oil at different points (hot-spot) and detection of failure can be achieved through measurements of vibrations of the magnetic laminates and windings [1].

Sensors developed for the environmental conditions inside power transformers must withstand high electric and magnetic fields and a wide range of temperatures (150 °C in load). The technology of OF sensors satisfies these conditions well; optical fibres are also able to access the sensing region maintaining conditions of isolation.
However, it is worth mentioning that the amplitude of the measurands is often very small, so high-sensitivity solutions are required. In this case, the features of interferometric-based sensors are unique [2]. The characteristics of the vibrations which constrain the design of the sensor are as follows. Firstly, the vibrations, which are due to deformation of elements or displacement between them, are in the range of up to a few nanometres. Secondly, the main frequency, 100 Hz, is too low for many types of dynamic measurement, but important information is also found at its harmonics (10th harmonic) [3], so most specific frequency-dependent solutions are of no use.

Under these conditions, potential measurement techniques are based on sensing dynamic strain/displacement in contact with the core and the windings. Results obtained using an interferometric OF intrinsic transducer are actually available, thanks to its high sensitivity [4]. In fact, the length of the sensing head enhances this sensitivity. Other techniques, such as those based on Bragg gratings [5] and fibre Fabry-Perot interferometry [6], are not of comparable sensitivity to the available technology [2, 4]. Different OF sensors, Bragg gratings, Fabry-Perot and fluoroptic methods have been proposed for temperature measurement inside transformers [7, 8], but, to the best of our knowledge, no attempts have been made to focus on vibrations within this application.

Several works have applied OF sensors to the measurement of vibrations in rotating electric machines [9–12]. Such sensors are mainly based on the intensity modulation of the light in a cantilever configuration. However, higher sensitivity and broader bandwidth of the sensor are required for the typical amplitude of vibrations found in transformers. Difficulties also arise when the installation is in contact with the elements inside, which is not the case with a simple intrinsic optical fibre. OF sensors work well in rotating machines in electric power generation, where the vibrations are quite long and occur at low frequencies. However, at present the only techniques able to fulfil the sensitivity requirements needed for measurement of the small amplitude of vibrations found inside transformers are interferometric techniques [4].

The main objectives of our research are to develop a measurement system for monitoring the vibrations at the core and windings of a power transformer. We have proposed an OF interferometric technique for this purpose [13]. We have also obtained results in a medium-power transformer (25 kV A) with a 10 mm long probe bonded to the core [3, 4]. An extensive discussion is reported in [4] about the feasibility of a practical design for an interferometric sensor for industrial applications, which deals with improvement of the sensitivity through the design of the sensor head until a multifringe interference output is obtained, and the realization of synchronous demodulation with an unambiguous multicycle signal.

Our main objective is to monitor the high-power transformer at the experimental plant of the FUTURE project with Unión Fenosa SA. In this context, piezoelectric accelerometers emerge as the best commercially available alternative. Comparative analysis of both sensors is therefore presented for typical vibration amplitudes and frequencies. As well as the immunity to electromagnetic fields and the isolation properties of optical fibres versus electronic sensors, the high sensitivity of the interferometric measurement and the quality of performance of the OF sensing system is also very important. Therefore, our results also include comparisons with other sensors.

In this paper we focus on the calibration of OF interferometric probes designed for this application with magnification of transduction. The study is based on two experiments: firstly, calibration of the increased sensitivity compared with that of a commercial accelerometer. Then, the performance of the sensor is evaluated while measuring the physical vibrations of the transformer core, thereby obtaining the dynamic magnetostriction transference function of the magnetic laminate material. Both experiments confirm the feasibility and quality of the new OF interferometric design together with the limitations of other sensing solutions. On-site demonstrations are given for two power transformers and for two regions, the core and the windings, with different vibration sources: magnetostriction in the core laminates and the displacement between the constitutive elements of the windings.

The paper is organized as follows. Section 2 is devoted to the principle of operation and the basis of the improved sensitivity and multifringe interference output together with a discussion of benefits and expected limitations. In section 3 the calibration set-ups are described together with their optoelectronic arrangements and laboratory tests. Experimental results and a comparative analysis are also included here. They focus on high-performance interferometric calibration tests and characterization using a low-power transformer. The installation inside two power transformers, the set-up on-site and the vibration measurements with the OF interferometric sensor are presented in section 4. The experimental results include those for the core and windings. Finally, there is a discussion of our conclusions in section 5.

2. Optical fibre interferometric sensor

The sensing probe is a piece of OF which is either in contact with the vibrating surface or fixed at its extremes to the elements undergoing relative displacement; these situations cover the two main cases of vibrations occurring inside a transformer (figure 1). For example, vibrations at the core are produced by deformation of the laminates. On the other hand, vibrations at the windings are mainly due to the relative displacement of adjacent blocks of conductive coils. Figure 1 shows our design for the sensing probes with two schematic details. The fibre is bonded completely to the surface in the first case, detecting its deformation (figure 1(a)). In the second case, the extremes of the fibre are bonded to two blocks whose relative displacement will be detected (figure 1(b)). In both cases the fibre senses the vibrations through its elongation and in terms of optical phase. Since a piece of OF of defined length is used for detecting the vibrations as a change in length, the sensor could also be analysed in terms of dynamic axial strain [14].

Moreover, the sensitivity of the sensor is proportional to the length of fibre exposed to the measurement field. Thus, by designing the sensor head accurately, sensitivity could be enhanced while maintaining a compact solution. For this purpose, the sensor head is composed of a number of parallel segments made by coiling the same bare fibre, thanks to its
The transducer efficiency, and extremes of linking (figure 1).

Small diameter (figure 1). In this way, the strain detected with a fixed gauge length is magnified by the number of segments.

Taking this into account, the translation of the vibrations onto the optical fibre sensor is characterized by the optical phase change, $\Delta \phi$, as a function of the changes in fibre length, $\Delta L$, produced by the deformation or displacement:

$$\Delta \phi = \frac{2\pi n \Delta L}{\lambda} \xi \eta.$$  \hspace{1cm} (1)

Practical sensing of several parameters could be assumed through interaction with $\Delta L$, but in this case it is only related to the strain at the fibre segments. The terms involved are the refractive index $n$ and the wavelength of the light, $\lambda$, from a laser source. Three additional terms are considered: $\xi$ is related to the strain-optic properties of the fibre, $\eta$ is related to the transducer efficiency, and $M$ expresses the magnification of sensitivity with the number of parallel segments, and generalizing, with the fibre sensing length used. The terms $n$ and $\xi$ are well known for silica fibre and are considered constants for this case [14], and the wavelength is $633 \text{ nm}$ of the He–Ne laser.

The transducer efficiency is experimentally evaluated and represents the strain transfer from the surface to the fibre. It was found to have a value of about 0.65 with the segments completely bonded to the surface [4], and it reaches a maximum value (unity) for free segments except at the extremes of linking (figure 1).

The optical phase change of the light crossing the fibre is interrogated with a Mach–Zehnder interferometer whose arms are the described sensing fibre and a stable reference one (figure 1). A photodetector is focused onto the main disc on the fringe pattern resulting from combining the light beams of both single-mode fibre outputs. In this case, the interference intensity is:

$$I(t) = I_o[1 + V \cos(\phi(t))]$$  \hspace{1cm} (2)

where $I(t)$ is the intensity with time, $I_o$ is the mean output at the photodetector, $V$ is the visibility and $\phi(t)$ is the optical phase shift with time, which involves initial conditions and the optical phase change as in equation (1) [4]:

$$\phi(t) = \phi_0 + \phi_D(t) + \phi_{MV}(t).$$  \hspace{1cm} (3)

In (3), $\phi_0$ is the initial phase difference between reference and sensing fibres, and is a constant term, $\phi_{MV}(t)$ represents the sensing signal due to the mechanical vibrations inside the transformer, which is periodic, and $\phi_D(t)$ is the term indicating disturbance. This last term is mainly a very low-frequency random drift of the optical phase which is related to the stability of the optical paths of the interferometer and to the response of the fibres to thermal changes. Its impact is far slower than the dynamic behaviour of the vibrations. However, it modifies the quasi-static initial optical phase and the sensitivity to the dynamic parameter.

The magnification provides increased sensitivity of the intrinsic fibre compared with the in-fibre impressed cavities and gratings [2]. Furthermore, it allows displacement of multiple fringes to be registered by the interferometer ($\Delta \phi > 2\pi \text{ rad}$), instead of a typical small signal of phase ($\Delta \phi \ll 2\pi \text{ rad}$) modulating the intensity around the quasistatic initial optical phase ($\pi/2$ or $3\pi/2$ rad). With this approach, a multifringe output is considered: $\cos^{-1}$ processing is found to be useful and is accomplished with an extended range through the technique of counting (the number of $\pi$ rad periods) and fraction excess for several cycles.

This presents some benefits for extracting the optical phase, i.e. obtaining a sensor output which is linear to the vibrations, without the need for additional external modulation. First, as with most kinds of optical phase demodulation technique, the $\cos^{-1}$ processing is dependent on the intensity amplitude considered within the visibility, $V$, which is independent of the transduction onto $\phi(t)$. But, since consecutive values of $I(t)$ corresponding to $k2\pi \text{ rad}$, $k \in [0, 1, \ldots]$ are always available, the intensity could be normalized to the maxima and minima at least once in each optical phase period, thus correcting the visibility changes that affect the $\cos^{-1}$ processing and other amplitude-dependent methods of phase detection. We should remember that the visibility changes are far slower than the changes in vibration and temperature. Furthermore, note that the dynamic change of phase can also be obtained independently from the different possible initial conditions. Therefore, the
In fact, the magnetic field is modulated in quadrature with the voltage; the magnetic forces are therefore maximum when the voltage excitation becomes zero, and the mechanical response of the material is independent of the sign of the magnetization. Consequently, the dynamic strain related to the vibrations has a rectified shape with respect to the voltage input [4, 16]. Note that each fringe displacement starts with a peak, valley or zero-crossing of the reference. This allows the determination of the sign of the displacement for the dynamic intensity output and solves the ambiguity of the periodic signal. This synchronous concept also applies to vibrations at the windings.

Figure 2(b) is an expansion of figure 2(a) showing the abovementioned synchronism and signal processing of the multifringe interference output in detail. The magnetization of the core is zero at I and III where the voltage reaches its extremes. It increases to its maximum from I to II, and decreases from II to III. Therefore, the fibre length increases with core elongation due to the magnetization (I–II) and then decreases (II–III). The sensor read-out is the evolution of the respective optical phase with time, which is obtained by processing the interference output between two consecutive marked points (figure 2(b)). The direction of the fringe displacement is considered by changing the sign of the optical phase first derivative at these points. A magnetization valley is reached at IV. However, since the magnetostriiction responds with the same sign to a positive or negative magnetization, the fibre elongation and the respective optical phase increase from III to IV, as is observed from I to II. Then the process starts up again.

An important issue with this processing method is that the read-out of the fibre elongation is obtained independently of the initial conditions, thus overcoming difficulties caused by the drift ($\phi(t)$ at equation (3)). This drift is observed in figure 2 as a change in the initial point from which the fringe displacement starts in any semicycle. Note that the initial conditions and the dynamic component due to vibrations are clearly identified and distinguished in the output of the interference intensity.

### 3. Interferometric calibration and comparison with accelerometers

The comparative analysis and calibration were developed in two ways, represented by two experiments. Firstly, a free-space Michelson interferometer with a controlled moving arm was used as a master reference to measure the dynamic displacement. This scheme is widely used for the calibration of accelerometers. Secondly, one especially significant case for the present application is the comparison of the output of two sensors for the core vibrations of a low-power transformer. In this case, the dynamic transference function of magnetostriction was obtained precisely using the fibre sensor.

The comparison with piezoelectric accelerometers is required because of the possibility of using them in the application instead of other developments. First of all, they offer characteristics such as easy installation, robustness and availability that other alternatives do not have. However, there is some uncertainty about their immunity, isolation and precision inside the transformer. Nevertheless, the main limitations are concerned with the sensitivity and accuracy.
The piezoelectric accelerometers were taken into account in the piezoelectric tube, D: photodetector. An optical fibre interferometric sensor was carried out. However, the piezoelectric accelerometers were taken into account in order to obtain a comparative analysis as well as for the characterization of the novel fibre sensing concept.

### 3.1. Interferometric calibration

We implemented a sensor calibration scheme that has two interferometers for measuring both responses to the same stimulus at the same time. One is a free-space Michelson interferometer with a piezoactuator (PZT) installed in one of the arms, and the second interferometer is an OF Mach–Zehnder scheme (see figure 3). In the Mach–Zehnder interferometer the OF sensor is bonded to the PZT transducer. This PZT is a piezoelectric tube which is 360 mm long and is used for generating the vibrations. It supports the accelerometer and the moving mirror (see detail of figure 3) of one arm of the free-space Michelson interferometer. This interferometer is used to calibrate the displacement generated by the PZT accurately in real time. The elongation is about 250 nm in the tests, which is greater than the results of the tests at the core of a medium-power transformer [4] but within the expected range of strain at the experimental plant transformer (about 7 \( \mu \)ε, 36 mm PZT length). Considering the fibre sensor design, several segments are bonded to the PZT in the axial direction.

The PZT is excited with low-amplitude voltage signals (20 V peak to peak) which ensure a linear response. Frequencies from the main harmonic expected in the application (100 Hz) to the most significant bandwidth (4th harmonic) are used. Since real monitoring of the displacement is obtained with the Michelson interferometer, the frequency response of the PZT does not affect the experimental results (resonant frequency of 1.7 kHz). The OF probe is 25 mm in length \( \times \)10 segments of the single-mode sensing fibre and it is bonded to the PZT surface using cyanoacrylate (adhesive resistant to 125°C). The accelerometer is piezoelectric (4371 V, Brüel & Kjaer), its characteristics are 11 g, 42 kHz, 1.020 pC m\(^{-1}\) s\(^{-2}\) and it is conditioned with a charge amplifier (2692A 04, Brüel & Kjaer) from 31.6 mV m\(^{-1}\) s\(^{2}\) to 10 V m\(^{-1}\) s\(^{2}\).

The optical phase change obtained from the calibration interferometer is proportional to the PZT dynamic elongation that modifies the optical path through the moving mirror. The relation is \( 2\pi \) rad for each half wavelength (\( \lambda/2 = 633/2 \) nm). The optical phase change with the fibre interferometer is proportional to the elongation induced over each segment (25 mm) and magnified by the number of segments (\( M = 10 \)).

By comparing both optical phase outputs in units of strain, the fibre’s sensitivity is determined and the efficiency factor is derived. The elongation of the fibre (\( \delta x, \) nm) is related to the displacement of the moving mirror (\( \delta l, \) nm) through the strain produced at the PZT relative to the length of the fibre (\( X, \) mm) and the PZT (\( L, \) mm): \( \delta x / X = \delta l / L \) (\( \mu \)ε).

On the other hand, the accelerometer response (Acc) is related to the elongation \( \delta l \) through its second derivative in time. For a pure tone (\( \omega/2\pi \)), taking a harmonic displacement of the accelerometer \( \delta l(t) = \Delta l \sin(\omega t) \), then the acceleration is \( d^2(\delta l)/dt^2 = -\omega^2 \Delta l \sin(2\pi ft) \), and therefore, it is proportional to elongation in amplitude means through the square angular frequency (Acc = \( \omega^2 \Delta l \)). As a consequence, the output of the accelerometer is integrated twice in the experiments.

![Figure 3](image.png)

**Figure 3.** Experimental set-up for the sensor calibration. The free-space Michelson calibrator, the Mach–Zehnder interferometer with OF arms and the accelerometer are monitored at the same time. M: mirror, BS: beamsplitter, L: lenses, OF: optical fibre, PZT: piezoelectric tube, D: photodetector.

![Figure 4](image.png)

**Figure 4.** Results of the interferometric calibration at 100 Hz: (a) voltage input to PZT (10 V peak, 100 Hz), (b) interference output of the OF sensor (25 mm in length, \( \times \)10), (c) output signal of the Michelson free-space interferometer, (d) voltage output of the accelerometer (1 V m\(^{-1}\) s\(^{2}\)).
Figure 5. Calibration curve of the OF interferometric sensor for tests with 100 Hz inputs.

Figure 6. Harmonic decomposition of the output of two sensors with pure tone inputs of 100 Hz, in relative units (%) to the amplitude of the output at the main frequency (100 Hz). (a) OF interferometric sensor output is one order of magnitude better (\(\leq 0.12\%\) each residual harmonic) than (b) the accelerometer output (\(\leq 1.2\%\) each residual harmonic).

The harmonic decomposition of the vibrations is one of the main parameters for modeling transformer behavior in this application [17]. Thus we obtain the extinction ratio of each harmonic for a 100 Hz input, which is the most significant frequency in the application. Figure 6 shows the harmonic decomposition of both sensor outputs (OF interferometric sensor and accelerometer) expressed in relative units to the true harmonic amplitude (excitation of 100 Hz). The results obtained with the OF sensor show that each induced harmonic is less than about 0.12% of the excited main frequency. These values are in the range of actuator linearity and they are one order of magnitude better than the results obtained from the accelerometer (\(\leq 1.2\%\)). Also note that the errors at frequencies below the excitation are significant with the accelerometer, although high-pass filtering is typically used for softening its impact at the sensor read-out.

An extended treatment is presented in table 1, which shows the results for pure tone inputs of 200–400 Hz. It is expected that the accelerometer response would be better for higher frequencies because of the square dependence of the angular frequency. This is observed with harmonics higher than the excitation by 2 and 5% of its amplitude, while for the OF sensor response they are 0.3 and 1.2% respectively. Nevertheless, the most significant error is with the low-frequency induced components, which in this case always appears at 100 Hz (see table 1 (c)). Whereas the OF sensor output maintains the same level of extinction ratio, the accelerometer output shows incorrectly induced amplitudes (errors up to 20%), which affects the true level of the main harmonic in the application. As we can see, the performance of the OF sensor is at least one order of magnitude better than that of the accelerometer, and the precision obtained with the novel sensor is within the range needed for the application. More comparative results confirming this comparison are presented in the following with an implementation in a transformer.

3.2 Dynamic transference function of magnetostriction in a low-power transformer

It is desirable to check the aforementioned results in a real transformer, as well as against a well-known reference. Magnetostriction of the magnetic laminates of a transformer
The experimental set-up of the tests with a low-power transformer. Detail of the fibre probe in the axial direction for measuring the dynamic magnetostriction at the core laminates.

For this experiment we have selected an optical fibre probe which is the same as that which will be used in power transformers (30 mm long × 30 segments). In this case it is bonded to the magnetic laminates of a low-power transformer (770 VA) and installed in a Mach–Zehnder interferometer configuration.

The measurement of dynamic strain by the sensor related to the magnetic flux provides the transference function of magnetostriction. The voltage applied to the transformer was monitored as the reference (see figure 2), as it is related to the magnetic flux ($\pi/2$ rad out of phase) [4, 16]. Figure 7 shows the detail of the probe bonded to the transformer core surface. This arrangement monitors the axial axis of the magnetic laminates and is completely bonded to the surface in the fibre sensing region. An accelerometer with the aforementioned characteristics was also installed to monitor the vibrations in this direction.

The experimental results focus on the representation of sensor outputs with the voltage input. Since voltage and magnetic flux are in quadrature, and vibrations are at double the frequency of this excitation, the sensor output was inverted to simulate the $\pi/2$ rad out of phase of the 50 Hz reference. Thus, the lines depicted in figure 8 represent the dynamic transference function of magnetostriction in vacuum tests. In the case of the OF sensor, deformation of the laminates ($\mu\varepsilon$) is obtained as a function of the magnetic excitation. The other case is only used to compare the shape and reproducibility of both sensors, and it is given in units of the monitored displacement.

The optical phase is obtained from several fringes and the shape of the function follows the quadratic law to a first approximation. The dynamic strain sensed with this probe is about 4 $\mu\varepsilon$ with a resolution of better than $5 \times 10^{-2} \mu\varepsilon$ (1 mm in 30 mm). These results are in good agreement with this effect on ferromagnetic materials and indicate that axial fibre strain prevails. For an induction of 1.6 T, the strain is expected to be about 4.5 $\mu\varepsilon$ for the silicon steel alloy typically found in transformer cores. Higher induction saturates the core and magnetostriction characteristic [16]. The magnetic core in the transformer does not show saturation (figure 8), and the maximum strain obtained at 4 $\mu\varepsilon$ (axial strain) agrees with the predictions and static observations of [16]. On the other hand, the accelerometer output needs high-pass filtering to obtain this shape, and although the trend is similar to the results obtained with the OF sensor, the difference between the reproducibility and accuracy of the methods is clear (figure 8).

The characterized function shows that the dynamic strain of the laminates is mainly of double the frequency of the excitation and this harmonic dominates over higher-frequency components. We can observe that the material exhibits hysteresis but not saturation at this input level. The vibrations are clearly synchronized with the reference voltage signal applied to the transformer, thus the proposed optical-phase demodulation approach is demonstrated to be suitable for high-resolution measurements.

Table 1. Results of the residual harmonics at the output for pure tone inputs of 200, 300 and 400 Hz. In relative units (%) to the amplitude at the output of the true frequency component. Frequencies below 100 Hz are not considered, but they appear significantly in the accelerometer output.

<table>
<thead>
<tr>
<th>Testing frequency</th>
<th>200 Hz</th>
<th>300 Hz</th>
<th>400 Hz</th>
</tr>
</thead>
<tbody>
<tr>
<td>(a) OF: other harmonics</td>
<td>&lt;0.3</td>
<td>&lt;1.2</td>
<td>&lt;0.3</td>
</tr>
<tr>
<td>(b) Acc: higher harmonics</td>
<td>&lt;2</td>
<td>&lt;5</td>
<td>&lt;2</td>
</tr>
<tr>
<td>(c) Acc: harm. of 100 Hz</td>
<td>~16</td>
<td>~12</td>
<td>~20</td>
</tr>
</tbody>
</table>

Figure 7. Experimental set-up of the tests with a low-power transformer. Detail of the fibre probe in the axial direction for measuring the dynamic magnetostriction at the core laminates.

Figure 8. Transference function of magnetostriction at the core laminates (dynamic response). Results obtained in a low-power transformer with (a) the OF interferometric sensor (30 mm probe length, ×30) and (b) the accelerometer.
4. Experimental results in the application

Several OF probes with different configurations were installed inside two medium-power transformers, 25 kV A (medium-power tests) and 1.5 MV A (experimental plant of the FUTURE project), in order to monitor the vibrations at the core and windings. The complete process of installation and exhaustive description of the probes are beyond the scope of this paper, thus only those for which results are presented here will be considered. The first transformer was previously used to characterize the vibrations with a short length probe [4], but the results presented here relate to the improvement of the multifringe output and magnification of sensitivity approach. The second transformer is of interest in order to know the vibrations at the windings. The cores of both transformers are quite representative and of similar characteristics, but a typical configuration of the windings as separate blocks of conductive coils is only found in the second one (FUTURE transformer).

The characteristics of the fibres are as in the previous tests and at the same time the optoelectronic set-up reproduces the aforementioned Mach–Zehnder interferometer. Inside the transformers, access of the fibres is either through an available drill hole or with specific pass-through pieces and sealants designed for this purpose. The fibre probes are compared interferometrically with an external reference coil in both set-ups.

Figure 9 shows the details of two installed probes. The first is a sensor head in complete contact with the edges of the sheets 24 mm long and ~5 mm wide, which monitors the transverse deformation/displacement of the compressed core laminates. The length is constrained by the core width. The second is a typical sensor head 30 mm in length, also ~5 mm wide, bonded at its extremes to two main blocks of windings. It monitors their relative displacement. Both probes are made up of 30 paralleled segments for sensitivity magnification. These examples cover the demonstrations of the OF sensor at the core and the windings, as well as examples where it is completely bonded ($\eta = 0.63$, equation (1)) and fixed at its extremes ($\eta = 1$).

Figure 10 shows the results for the first probe. The synchronism reference is taken from the voltage input (zero-crossing and extremes). The tests are with nominal voltage in vacuum tests. Three significant signals are displayed: the moderate multifringe interference output, the voltage reference and the demodulated optical phase as the sensor output. They have been normalized for clarity. The wave shape of the vibration is rather more complex than that from the calibration tests with the low-power transformer since higher harmonics are observed. The interference output shows a displacement of more than five fringes each semicycle. The resulting amplitude is about 150 nm peak to peak which corresponds to 6.25 $\mu\varepsilon$ with the gauge length. It agrees with the expected values for the strain at the sheet borders compared with the axial strain at the laminates [4], which was also observed as being greater in the low-power transformer. The measurement resolution is better than 0.5 nm ($\sim 2 \times 10^{-2} \mu\varepsilon$) with this optical phase processing.

Finally, the results of vibrations at the windings are also presented. They are shown in figure 11 for tests with the transformer in load. They are depicted as in figure 10. A loading of 77% is used as a typical moderate working. In this case the interference output is of more than 20 fringes, which corresponds to a relative displacement of the order of 450 nm ($\sim 15 \mu\varepsilon$ of the fibre probe). It produces marked multifringe output by using the magnification ($\times 30$). The synchronism reference is also taken from a power-line voltage instead of the current at the windings. Therefore, there is a delay between the voltage reference applied to the transformer and the optical phase output. However, the optical phase frequency is twice the voltage frequency. The measurement resolution is even better than before because of the larger gauge length. Note that the characteristics of the shape and frequency of the vibration wave are similar to those for the core vibrations, therefore agreeing with the postulated principle of sensing.

5. Conclusions

A new interferometric OF sensor for measuring the vibrations inside power transformers was presented and evaluated. Complete calibration of the designed approach was obtained and compared with that of commercial accelerometers. The results demonstrate that the sensor performance is at least one order of magnitude better than those for commercial
accelerometers. This is especially significant with respect to the residual harmonic errors observed.

This comparative analysis can also be appreciated from the results obtained using a low-power transformer. A resolution of better than 1 nm ($5 \times 10^{-2} \mu \varepsilon$ in 30 mm) was achieved through the magnification concept applied to the interference output with a longer sensing fibre. This also provided an associated demodulation technique by taking advantage of the multifringe output and the synchronism with the electrical references available in the application. The results of the dynamic characterization of the magnetostriction in steel alloys of transformer cores are, to the best of our knowledge, the first such experimental measurements.

Finally, experimental demonstrations of the OF interferometric sensors are presented and discussed for measurements on site. The core and the windings are monitored inside two power transformers (25 kVA and 1.5 MV A) covering the two possible transducer arrangements: when it is completely bonded and when it is fixed at its extremes. According to the calibration, the sensor performs with a resolution of at least 1 nm. The magnification/synchronous approach is also proved to be accurate for a real application.

Acknowledgments

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