Eddy Current Crack Monitoring System for Structural Health Monitoring (SHM) Applications

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1 Abstract

The degradation of large metallic structures, such as bridges, oil platforms and penstocks is a serious concern for civil engineers. The ageing, application of cyclic loads and harsh environmental conditions, are among the main causes.

Material cracking is a clear and important indicator of degradation. The appearance of a crack on a critical structural element implies thorough and frequent controls. In such cases, the employments of an automated monitoring system constitutes a viable solution.

In this work, it is presented an innovative sensor for the monitoring of existing cracks on metallic structures. Compared to existing solutions, the proposed device is able to provide the direct information of the crack length. The principle of measurement is based on the Eddy current non-destructive testing. The technique does not require special surface preparation and is largely employed in industry and aerospace.

The analysis of extensive data gathered in the course of fatigue testing, highlights the sensor capability in providing a reliable measurement of the crack length. Furthermore, it is evidenced the possibility to determine the main parameters of the mechanical excitation and observe the thermal effects on the material.

Finally, the pending phase of sensors installation for the monitoring of a real bridge is introduced. This step will allow to assess the sensor performance in a real environment. The gathered data will be used for the development of tools aimed to maintenance planning and a real time estimation of the remaining fatigue life.

Keywords: Metal structures, Structural Health Monitoring (SHM), Conditional Based Maintenance (CBM), Non Destructive Testing (NDT), Crack sensor, Crack propagation, Bridges, Fatigue.

2 Introduction

As the bridge networks continues to age, Non Destructive Testing (NDT) becomes more and more important. Periodic inspections are always planned to assess the conditions of the structure. Commonly, visual evaluations are used to check the status of the parts considered most critical. In spite of its simplicity, this does not provide information on actual stress/strain levels, with the risk that some problems go unnoticed. At this purpose, NDT can be used to evaluate the severity of the damage and, in case an intervention is needed, the most suitable repair solution. Such approach allows a cost-effective maintenance based on the planning of repair and replacement strategies [1].

In general, the bridge design is conservative toward the safety resulting in heavy and costly structures. In some cases, the weight is a critical constraint and marginal safety factors are employed. For this reason, routine inspections are devised so that any damage can be promptly repaired. If a reliable monitoring is implemented, the frequency of inspections can be drastically reduced. In addition, this would allow to reduce the cost of material due to the overdesign for new constructions [2].

Old bridges have been required in the time to carry heavier loads with respect to the original design (i.e. increase of traffic, vehicles weight, etc.). In Europe, it is expected that the transportation of goods by rail will double or even treble within the next 20 years. The preparation of the infrastructures will see the employment of performance-based structural assessment. At this purpose, one possibility is the permanent instrumentation of the interested bridges. In this scenario, Structural Health Monitoring (SHM) should provide data to understand the performance and predict the durability of the structure. The needs for inspection and sensor generated data justify the need of efforts to establish new performance and condition monitoring services [3].

Due to the increasing loading conditions, the fatigue is one of the major concerns in metallic bridges and there is need of tools for its evaluation. It has been shown that the entire reparation of a bridge can have a comparable cost of a new construction. In contrast to this aspect, the replacement of a bridge is not always sustainable due to environmental, balance or historical landmark reasons [4].

Research and case studies of in-service fatigue cracking over the past 40 years have helped in formulating design guidelines to limit fatigue cracking in new constructions. The necessity of structural data and the presence of aged bridges support the utilisation of monitoring systems [5].

The life of a mechanical element is typically evaluated in term of number of stress cycles (S-N). At this purpose,
the stress concentration can be quantified with numerical simulations. These suffer of uncertainty and the estimation can differ substantially from reality. Hence, fatigue evaluation using direct measurement of stress and strain proves to be more accurate and efficient [6]. This underlines again the importance of NDT. In spite of the great benefits, these solutions present some limitations. These could require the bridge to be closed, they cannot work in all environments or they require qualified and trained personnel to perform the measurements. For this reason, the SHM - thanks to the advancement in sensing and data acquisition technology – has gained applications in civil engineering in the past decade becoming an accepted solution to diagnose bridge conditions. [7].

A recent case study, performed in the course of the European project “FADLESS”, showed the successfully employment of monitoring data. The evaluation of almost 1.5 years of measurements allowed the evaluation of local fatigue effects on a metallic riveted bridge [8].

The survey of literature highlights a clear interest in the instrumentation of bridges for structural monitoring purposes. A report realised in the framework of the European project “Sustainable Bridges” in the 2007, remarked the availability and maturity of the technology for the realisation of SHM solutions based on networks of different sensors [9]. As a matter of fact, it is possible to find recent publications describing smart sensors for the application in the SHM field [10][11][12]. The available solutions concern in general the employment of standard NDT techniques. These includes mainly the measurements of accelerations (for modal analysis) or strain (deformation and stress quantification). The sensors are applied to the elements considered more critical as part of a network; the measurements then requires processing and analysis of experienced personnel.

In spite of the major trend, other solutions attempt to directly evaluate the crack growth. The direct evaluation of this parameter is desirable to predict crack extension and remaining fatigue life. It is possible to extract this information, for example, utilising stress or acoustic emission measurements. On the other hand, this implies complex algorithm and procedure for the treatment of the data, which must be carefully selected to achieve sufficient robustness [13], [14].

The review of literature reveals the lack of results concerning the employment of sensors able to provide a direct interpretable estimation of the crack growth. The presented research is addressed to the development of a novel sensor, intended for SHM applications. The device is conceived, principally, to measure the length of surface cracks of metallic structural elements. Additional sensors are also integrated to enable supplementary studies.

2.1 Contents
In section 3 the basic concept of non-destructive testing with the Eddy current principle is explained. Then, the features of the realised device are introduced

In section 4 are reported experimental results concerning the application of the developed sensors for the measurement of crack growth. The application on a specimen in the course of a fatigue test is shown.

In section 5 it is described that scenario for the installation of a SHM solution on a real bridge.

3 Measurement technique

The proposed solution takes advantage of the generation of Eddy current. The key advantage of this technique is that it does not require surface contact or preparation. For this reason, the technology is largely employed for crack detection in industrial and aerospace fields [15] [16] [17].

3.1 Theoretical background

This section introduces elementary concepts required for a comprehension of the NDE with Eddy currents.

When an alternating energized coil approaches a conductive element, the penetration of the alternating magnetic field will cause the induction eddy currents in the material (Figure 1). The so induced currents will create a secondary fields; this opposes the primary field [18]. The measurement of the coil impedance is affected by this phenomenon. The value changes depending on material properties, such as conductivity \( \sigma \) and magnetic permeability \( \mu \). The presence of a crack, at same extent, can be seen as an abrupt change of the local material properties.

Typically, the real and imaginary part of the impedance are reported as normalized quantities on a complex plane with respect to the measure in air, an example is reported in Figure 2. This representation is used during inspections when a coil is scanned over a surface of interest. Different phenomena, such as the coil lift-off (removal from material) or the passage on a defect, can be noticed observing the different trajectories.

Figure 1. Generic representation of Eddy current induction principle.
3.2 Device description

The device has been conceived to be lightweight, compact and flexible to allow its installation on curved surfaces and in limited space as well as optimise the surface coverage. These features, and the nature of the measurement principle, allow the sensor fixation on the surface to monitor with a simple sticky band.

In addition, the system is equipped with thermal and acceleration sensors, resulting in a multi-physics platform allowing to acquire relevant environmental parameters at the same time and perform adequate signal compensation (e.g. for temperature) or correlation (e.g. with vibrations). This opens the door to further studies such as the influence of vibrations on crack propagation and ultimately to full “sensor fusion”.

In Figure 3, it is presented the layout of the device with its constitutive elements. The full integration of the electronics allow a direct connection to a PC or another acquisition system with data rate up to 1 kHz. In addition, the presence of a microcontroller enables a direct processing of the signals easing the data interpretation. In this fashion, the provided output includes the direct information of the crack length avoiding the necessity of complicated post-processing.

More details concerning the device ratings are listed in Table 1.

3.3 Crack length reconstruction principle

The length calculation exploits the combination of the impedance measurement of an arrangement of contiguous coils. These are disposed on a surface and aligned to the path of crack propagation. The concept is here explained for a linear array of elements. In Figure 5 it is shown the time evolution of a crack length. It is assumed that the crack propagates crossing in sequence the various coils (top graph). The presence of a defect influences the measured impedances. Ideally, this value is confined within two limits labelled as “no crack” or “full crossing” respectively. Therefore, once is known the single coil geometry, it is possible to step backward and recalculate the crack length using the impedance information. This strategy is used to process the signals in the experimental section.

The same principle can be easily extended to a matrix arrangement of sensing elements. This implementation, in spite of the major complexity, avoids the need of crack alignment. This aspect is part of future works.

Table 1 Device ratings.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Supply voltage</td>
<td>5 to 60</td>
<td>V</td>
</tr>
<tr>
<td>Max. power consumption</td>
<td>0.9</td>
<td>W</td>
</tr>
<tr>
<td>Average power consumption</td>
<td>0.5</td>
<td>W</td>
</tr>
<tr>
<td>Communication class</td>
<td>USB, RS422</td>
<td>-</td>
</tr>
<tr>
<td>Nominal data rate</td>
<td>1</td>
<td>kHz</td>
</tr>
<tr>
<td>Operating temperature</td>
<td>-20 to 70</td>
<td>°C</td>
</tr>
<tr>
<td>Dimensions (L x H x W)</td>
<td>165 x 25 x 3(0.1)</td>
<td>mm</td>
</tr>
<tr>
<td>Weight</td>
<td>20</td>
<td>g</td>
</tr>
<tr>
<td>Minimum radius of curvature</td>
<td>0.8</td>
<td>mm</td>
</tr>
<tr>
<td>Crack length resolution</td>
<td>100</td>
<td>µm</td>
</tr>
<tr>
<td>Coil width c</td>
<td>15</td>
<td>mm</td>
</tr>
<tr>
<td>Number of EC sensing elements</td>
<td>4</td>
<td>-</td>
</tr>
<tr>
<td>Dimension of single EC cell</td>
<td>15 x 20</td>
<td>mm</td>
</tr>
<tr>
<td>Acceleration range</td>
<td>±2</td>
<td>g</td>
</tr>
<tr>
<td>Acceleration resolution</td>
<td>2×10⁻³</td>
<td>g</td>
</tr>
</tbody>
</table>
4 Application to fatigue test

The device is applied on several specimens in the course of high cycle fatigue testing. These experiments were being conducted at the ICOM EPFL in the contest of a thesis work related to crack growth threshold.

The specimen consists of a steel S235JR symmetrical flange tip attachment (Figure 7). This part is used for the manufacturing of orthogonally welded beams. The element is subjected to block loading, the mechanical parameters of the different excitation cycles are collected in Table 2.

In this context, it has been possible to collect more than 350 hours of measurement.

4.1 Experimental setup

A snapshot of the experimental setup is shown in Figure 6. The specimen (2) is constrained to a fixed basement (6) and on the other side to a hydraulic actuator (1) that exerts a variable force in the vertical direction. The sensor (5) is applied on a preformed crack in order to track its evolution. An additional accelerometer (3) is also fixed on the actuator. The control unit (4) gathers the data.

The detail of the installed sensor is depicted in Figure 8. The device can be easily positioned with the aid of a sticky tape. The results presented in the next section are referred to this case. The three coils that observe the defect growth are labelled in sequence as s1, s2 and s3. The device is installed on a preformed crack which features a length of 27 mm. The sensing elements are oriented to the propagation direction; the coil s1 starts partially overlapped to the flaw. The acquisition was stopped after 8 hours since the specimen was approaching failure.
4.2 Data analysis

In this section are presented the collected data during the fatigue test. For each sensing element (s1, s2 and s3) it is obtained a time history of the impedance Z,

\[ Z(t) = R(t) + j\omega L(t), \]

where \( R \) and \( L \) are the resistance and inductance of the coil. These varies in time depending on the power dissipation and the magnetic properties of the tested material. The \( \omega \) is the electric excitation frequency.

For the graphical representation, it has been chosen to normalise \( Z \) with respect to the measurement in air \( Z_{\text{air}} \). The following variables are introduced

\[ Z_R = \text{Re}(Z)/\text{Re}(Z_{\text{air}}), \]
\[ Z_I = \text{Im}(Z)/\text{Im}(Z_{\text{air}}). \]

It holds the proportionality

\[ Z_R \propto R \]
\[ Z_I \propto L. \]

With reference to the start of the acquisition (t0) and the end (t1), the acquired signal presents the following states

- s1: partial crossing at t0, full crossing at t1
- s2: no crack at t0, full crossing at t1
- s3: no crack at t0, partial crossing at t1

The raw data spectrum features frequency components related to the different phenomena. These can be identified mainly as the crack propagation, thermal fluctuation and the mechanical excitation. The defect growth features a relatively slow time growth. Thus, for this study, a low pass filtering with bandwidth of 1Hz is applied.

The time plots of the quantities of interest are reported in Figure 9 and Figure 10. It is noticed, as expected, that the crack propagation implies a drop of the resistance. Since the specimen is made of magnetic steel, at the same time it is perceived an increase of inductance. Both these quantity are always larger than the reference value in air.

The same values are reported in a normalized complex plane in Figure 11. For sake of clarity, an offset on \( Z_R \) is added to s1 (-5\%) and s3 (+5\%), in order to avoid complete superimposition. It is observable a similar trend for the three paths. Moreover, the curves tend to the same end point as the crack propagates. The first and last point of acquisition are labelled with t0 and t1 respectively. Evidently, only the signal s2 exhibits a full propagation path.

4.3 Results: crack propagation

According to the principle presented in section 3.3, the crack propagation trend is estimated using the impedance evolution over time. First of all, it is introduced the constant

\[ K_x = |\text{Re}(Z_0) - \text{Re}(Z_1)| \]
\[ + |\text{Im}(Z_0) - \text{Im}(Z_1)| \]

which express the maximum impedance variation among the two levels, respectively when no-crack is present (\( Z_0 \)) and when the crack is full crossing the coil (\( Z_1 \)). Then, for each time sample of the \( i \)-th coil, it is calculated the value

\[ \Delta Z_i(t) = |\text{Re}(Z_i(t)) - \text{Re}(Z_1)| \]
\[ + |\text{Im}(Z_i(t)) - \text{Im}(Z_1)| \]

Table 2. Excitation cycles applied to the specimen.

<table>
<thead>
<tr>
<th>N [-]</th>
<th>( \Delta \sigma ) [MPa]</th>
<th>R [-]</th>
<th>F [Hz]</th>
<th>( \Delta \sigma/\Delta \sigma_{\text{max}} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>800</td>
<td>100</td>
<td>0.1</td>
<td>5</td>
</tr>
<tr>
<td>B</td>
<td>12500</td>
<td>40</td>
<td>0.74</td>
<td>15</td>
</tr>
<tr>
<td>C</td>
<td>29600</td>
<td>30</td>
<td>0.63</td>
<td>15</td>
</tr>
</tbody>
</table>

Figure 10 Imaginary part of the normalized impedance.

Figure 11 Relative impedance of the sensors in the complex plane. The crack propagation direction is highlighted. For sake of clarity, the curves s1 and s3 are shifted of 5\% on the real axis in opposite directions. The values t0 and t1 indicated the start and the end points of the curve.
that is the instantaneous distance to the full propagation state. Subsequently, the crack length measured by each coil can be calculated according to

\[ l_i(t) = \frac{c_w}{K_{x}} \Delta Z_i(t) + c_w \]  

(8)

where \( c_w \) is the coil width in the direction of propagation.

Applying the described procedure it is obtained the graph in Figure 12. It is noticed that the growth rate of the measured crack becomes faster with time. The signal of the third sensor, s3, shows the steepest slope. The coil s2 starts to sense the crack propagation after 3 hours, while s3 after 7 hours the acquisition was initiated. Among 5 and 6 hours s2 exhibits a slight local decrease of the propagation speed.

Subsequently the overall crack length can be obtained summing the different contributions, after this operation it is obtained the graph in Figure 13. Finally, the curve is merged to a set of manual measurement of the crack length performed in the course of the entire test. These values cover almost 200 hours of testing. The sensor instead was maintained operative for approximatively 8 hours, after 170 hours from the starting. During its operation was not possible to directly access to the crack. For this reason, in this span of time it is not possible a direct comparison. The plot of the overall time history is depicted in Figure 14. The complete data set appear to be consistent and without any discontinuity.

\[ \text{Figure 12 Crack length calculation for each separate coil.} \]

\[ \text{Figure 13 Reconstruction of the overall crack length.} \]

\[ \text{Figure 14 Merge of the reconstructed crack length with the manual measurements. The overall trend shows a good matching.} \]

4.4 Results: excitation analysis

In Figure 15, it is reported the complex plot relative to s2. Few seconds of the raw data in three representative situations are superimposed to this trend. The studied cases correspond to (A) no defect, (B) partial crack and (C) full crossing crack.

The Principal Component Analysis (PCA) is used to estimate the amplitude and orientation angle (referred to the vertical) of these clouds of points. It is observed that the crack propagation involves a rotation of the oscillation direction accompanied to an amplitude reduction. The data clouds exhibits in any case a preferential elongation over the imaginary axis (i.e. linked to inductance).

Such response appear to be related to the modification of the magnetic properties of the steel due to stress concentration and plastic deformation. This complementary analysis could constitute a notable advantage for the detection of stress concentration on magnetic steels.

Future studies will be devoted to clarify this aspect more in detail.
The non-filtered impedance presents harmonic contributions related to the mechanical excitation. The application of a Fast Fourier Transform (FFT) allows to determine the excitation frequencies. The estimation of the amplitudes is instead not accurate as non-linear effects are present. Anyway, the availability of the acceleration provide a valid alternative. The FFT results are reported in Figure 16 and Table 3. The obtained values are consistent with the real load parameters. It is worth to notice that further studies can be potentially integrated exploiting the measure of the acceleration. Methods like miner, rain-flow, or the analysis of Power Spectral Density (PSD) can be used for a real time evaluation of the load spectrum.

4.5 Results: thermal drift

The analysis of additional data sets collected over a long time acquisition evidenced an oscillatory mode with a period of 24 hours. The variation affects more noticeably the real part of the impedance as reported in Figure 17. The effect corresponds to a variation of the specimen resistivity due to the excursion of the room temperature over one day (17 to 22 °C). If necessary, the effect could be directly compensated exploiting the information of the thermal sensor. In any case, the information find application for the estimation of the thermal distribution, for example, when a set of sensor is installed on different points of a wide structure.

5 Bridge Structural Health Monitoring

At the time this manuscript is written, a set of the described device is being deployed on a steel bridge. In this scenario, the solution aims to provide to the structure owner, a continuous information of the evolution of monitored cracks. Normally, periodic inspection are planned to manually measure the defect progression. This point constitutes the effective employment of the realised device for SHM.

The concept is schematised in Figure 18. A network of sensors (1) installed on documented crack performs a continuous length measure. The data are stored and made available through a web interface (2). In addition, the system is able to generate periodic reports and trigger alarms. This action can be performed whether the measured length overcame a certain threshold or the growth rate becomes dramatically fast.

In Figure 19, it is reported the detail of a typical defect of interest for a monitoring application. It can be observed the surface is neither flat nor smooth. The proposed solution can fit to this situation as it is conformable to curved surfaces. Furthermore, it does not require any surface preparation limiting the installation efforts.

The analysis of gathered data will enable an efficient
maintenance planning based on the real structural health (Conditional Based Maintenance). Additionally, it will provide a realistic assessment of the achievable performance for an outdoor system.

In a successive phase, it is planned the development tools for an efficient fusion of the different information, mainly the crack growth rate and the load spectrum, for the prediction of the remaining fatigue life.

![Figure 18](image1.png)

**Figure 18** The proposed concept for monitoring application: (1) installation of a network of sensors on documented cracks on the structure, (2) data gathering with remote availability; automatic reporting and alarm generation.

![Figure 19](image2.png)

**Figure 19.** Typical critical defects where the application of the monitoring system can constitutes an advantage. (Courtesy of Bächtold and Moor).

6 Conclusion

In this paper, the concept of a novel sensor is introduced, which allows for direct measurement of crack length in metallic structural elements.

The application of the device to specimen subjected to fatigue testing evidenced the capability to obtain reliable information on the crack evolution. Nevertheless, the obtained data evidenced dependencies to the mechanical excitation and thermal variations. The possibility of exploiting such information for more advanced data analysis is described. This includes, for instance, the study of the acceleration frequency spectrum. Moreover, the potentiality for an online mechanical load spectrum reconstruction is also possible.

Finally, the scenario of the application of a network of sensors on a real bridge is described, which is currently under installation. Some remarks about the suitability of the technology for such field applications are made.

Additional efforts will be devoted to improve the technology and extend its use range. The main goals include:

- Analysis of measurement data collected on the bridge in real conditions
- Design of matrix sensing elements to allow a blind positioning of the device, i.e. not knowing a priori the precise location and direction of crack propagation
- Optimisation of crack length reconstruction accuracy
- Integration of algorithms for online load spectrum reconstruction and remaining fatigue life estimation
- Study ways to estimate the crack driving force (stress field variation in front of crack).

7 Acknowledgments

The authors would like to thanks in particular: PhD. Claudio Baptista from ICOM-EPFL lab for allowing to perform measurements on the running fatigue experiments; Sensima Inspection for the support in the sensor development.

8 References


