Load adaptive baseline by inverse Finite Element Method for structural damage identification

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Abstract

This work proposes a methodology to perform structural health monitoring by taking advantage of the inverse Finite Element Method (iFEM). The iFEM methodology is based on the minimization of a weighted least-squares functional defined as a comparison between the experimental and the corresponding numerical strains, enabling the reconstruction of the strain field of a structure through a limited number of sensors. Structural health monitoring is then performed by identification of discrepancies between the strains reconstructed by the iFEM and the measured strains. In particular, an anomaly index able to represent the actual health state of the structure is defined based on a comparison between the strain read at a target sensor location and the one reconstructed, in the same position, through the iFEM algorithm. This index enables to identify both the presence and the position of a fatigue crack damage. Furthermore, it is not dependent on the modelled boundary load condition but just on the health state of the structure. Though the formulation of the diagnostic problem is general for an arbitrary component geometry and damage type, the proposed method is numerically demonstrated by means of a cracked plate under different type of loads.

1. Introduction

Structural safety is a crucial aspect in many engineering fields and applications, from the mechanical and aeronautical components to the large civil infrastructures. In this framework, structural Health Monitoring (SHM) aims at reducing maintenance costs and increasing, at the same time, the structural safety by identifying the health state of a structure on the basis of data collected by on-board sensors.

Many SHM methodologies exist in the literature, either data \cite{1} or model -based \cite{2}. Data-driven methods rely on pattern recognition or machine learning to infer the health state of a structure directly from measured data, without recurring to physics-based models \cite{3}. On the contrary, model-based identification relies on simulated signal features for both the healthy and damaged conditions, to statistically diagnose the structural condition \cite{4}. However, several complications limit their implementation in the industry, and the variability of operational and environmental conditions is one of the most challenging \cite{5}. Operational loads can be naturally variable for many structures,
e.g., the aerodynamic loads on aircraft wings, bridges and high-rise buildings, and are generally an unknown input variable in many engineering problems. Furthermore, the structure's mechanical behaviour as well as the feature extraction from the recorded signals are markedly affected by the operational variability [6]. As a consequence, the unknown, or the un-modelled, variability of signal features might hamper the SHM system ability to detect a damage, potentially producing many false alarms [7]. In this context, a lot of studies are available in the literature aiming to reduce operational and environmental influences, usually referred to as data normalization [7]. Some methods make use of regression and interpolation techniques to fit the correlation of any measured feature with the varying operational or environmental condition [8][9]. However, their application is limited to situations in which a direct measure of the varying operational parameters is available. When a direct measure of the latter is impractical, other methods exist which are based on a feature’s shift, induced by damage, orthogonal with respect to a reference normal condition space. Among them singular-value decomposition [10], auto-associative neural networks [11], factor analysis [12] and cointegration [13] are examples of the current state of the art solutions. However, these methods require a large amount of data to guarantee that all the operational and environmental variations are covered during the algorithm training phase. Furthermore, if a wide range of variation due to operational variability is experienced by the baseline condition of the system, the damage will be hidden causing a delay in the alarm.

In this framework, a training-free methodology, the inverse Finite Element Method (iFEM), stands out for its peculiarities, allowing to reconstruct the deformed shape of a structure on the basis of discrete strain measurements. At a glance, it consists in minimizing in a least-squares sense a weighted error functional defined as a comparison between measured and numerically formulated strains. The procedure is computationally efficient, involving mainly matrix-vector multiplication, and fast enough for real-time implementation both in static and dynamic applications [14]. Furthermore, the knowledge of the applied load and the material properties is not required to reconstruct the displacements and the strain of the component, as only strain-displacement relationships are involved in the formulation [15][16]. The latter aspect can be exploited in a SHM framework, allowing to define a load-adaptive baseline taking advantage of the algorithm ability to automatically adapt its strain field reconstruction under different load conditions. Some works in literature also confirm the iFEM robustness against noisy measurements [17]. In fact, thanks to intrinsic smoothing operations in the iFEM procedure, an accurate displacement field reconstruction by the algorithm is achieved even in presence of noisy strain measures [18].

Despite the method attractiveness for SHM systems leveraging on strain field measurements [19][20], for which operational variability can dampen damage detection, very few applications of the inverse Finite Element Method to anomaly identification [21] are present in the literature. In this paper, the iFEM is thus used to define an anomaly index for a model-based damage detection and localization, independent from the loading condition and which could be exploited to define a load-adaptive baseline for damage identification. The anomaly identification relies on the concept that the iFEM reconstructs a strain field always compatible with the healthy model of the structure. If a non-modelled geometrical modification (e.g. due to damage) occurs in the monitored structure inducing a strain field perturbation, the iFEM algorithm will reconstruct a displacement field not compatible with the measured strains at test positions in the vicinity of the damage. The proposed methodology is numerically verified by the authors for a clamped plate
subjected to different loading conditions aiming to demonstrate the method’s independence from the operational load variability and confirming its attractiveness for future SHM implementation.

The paper is structured as follows. The general iFEM framework is briefly described in Section 2. Then, the iFEM output is used in Section 3 to define an anomaly index for damage identification. Section 4 provides information about the case study and the iFEM model for testing the methodology, while results are shown in Section 5 for the test case under different simulated load conditions. A conclusive section is finally provided.

2. inverse Finite Element Method overview

A brief summary of the iFEM approach to displacement and strain field reconstruction is provided in this section, while a more detailed description can be found in [14][22] for the interested reader.

The iFEM procedure consists in an optimization problem defined as a weighted least-squares variational formulation between measured (\( \varepsilon \)) strains and a numerical formulation (\( \varepsilon (\mathbf{u}) \)) of the same, with \( \mathbf{u} \) referring to the implicit optimization target: the displacement field. Supposing the structure is discretized in shell-like inverse elements, a weighted least-squares functional can be defined, accounting for membrane (\( \varepsilon \)), bending (\( k \)) and transverse shear (\( g \)) deformations of the element mid-plane, hereon referred to as reference plane. In particular, for the \( i^{th} \) inverse element, the functional takes the form:

\[
\Phi_i(\mathbf{u}^i) = w_m \left| \varepsilon(\mathbf{u}^i) - \varepsilon_{\text{m}}^i \right|^2 + w_b \left| k(\mathbf{u}^i) - k_{\text{b}}^i \right|^2 + w_s \left| g(\mathbf{u}^i) - g_{\text{s}}^i \right|^2
\]

where \( \mathbf{u}^i \) is the vector of nodal degrees of freedom in local coordinates and \( w_m, w_b, w_s \) are positive valued parameters associated to the membrane, bending and shear deformations, controlling the coherence between numerical and measured strains.

Two items are required for the implementation of the iFEM procedure. The first is the numerical formulation of the \( \varepsilon, k, g \) strain components which can be defined following a procedure similar to the direct FEM and not detailed here for brevity. The second is the definition of a vector of input strain measurements (\( \varepsilon_{\text{in}} \)) to be used for defining \( \varepsilon^i, k^i, g^i \). Considering the \( i^{th} \) inverse element instrumented with \( n \) strain sensors, each one measuring 3 strain tensor components and posed at \( n \) discrete positions \( \mathbf{x}_j = (x_j, y_j, \pm h) \) (\( j = 1, ..., n \)) on both the top (+\( h \)) and bottom (−\( h \)) surfaces, with \( h \) referring to the surface distance from the reference plane, the \( \varepsilon \) and \( k \) strain components can be computed as:

\[
\varepsilon_{i,j}^f = \frac{1}{2} \begin{pmatrix} \varepsilon_{xx}^f + \varepsilon_{xx}^- \\ \varepsilon_{yy}^f + \varepsilon_{yy}^- \\ \gamma_{xy}^f + \gamma_{xy}^- \end{pmatrix}_{i,j} (j = 1, ..., n)
\]

\[
k_{i,j}^f = \frac{1}{2h} \begin{pmatrix} \varepsilon_{xx}^f - \varepsilon_{xx}^- \\ \varepsilon_{yy}^f - \varepsilon_{yy}^- \\ \gamma_{xy}^f - \gamma_{xy}^- \end{pmatrix}_{i,j} (j = 1, ..., n)
\]

The strain component \( g \), on the other hand, cannot be directly computed from the measured surface strain components. However, since its contribution can be neglected in most of the engineering applications [22], the \( g \) formulation is neglected hereon.

Once the reference plane numerical (\( \varepsilon (\mathbf{u}) \)) and measured (\( \varepsilon^i \)) strain components are defined, a global system of equations can be derived as in eq.(3), applying a standard
finite element procedure to sum the contribution of the \( n_{el} \) elements in a single functional and then, minimizing it with respect to the global displacement vector \( \mathbf{U} \) and applying problem dependent boundary conditions:

\[
K_{FF} \mathbf{U}_F = \mathbf{F}_F
\]

where \( K_{FF} \) is a positive definite matrix always non-singular, assuring a solution of the system exists, and the subscript \( F \) indicates eq.(3) only includes the contribution of the unconstrained degrees of freedoms.

After the global displacement field is computed solving eq.(3), the reconstructed strain field (\( \mathbf{e}_{\text{iFEM}} \)) can be defined through eqs.(4):

\[
\begin{bmatrix}
\varepsilon_{xx} \\
\varepsilon_{yy} \\
\gamma_{xy}
\end{bmatrix} \equiv \mathbf{e}(u^i) + z \mathbf{k}(u^i)
\]

\[
\begin{bmatrix}
\gamma_{xz} \\
\gamma_{yz}
\end{bmatrix} \equiv \mathbf{g}(u^i)
\]

where \( z \) is the through-the-thickness coordinate. A model \( M_{\text{iFEM}} \) is, thus, available for real-time numerical prediction of the strain field \( \mathbf{e}_{\text{iFEM}} \) as a function of a vector of strain measurements \( \mathbf{e}_{\text{in}} \), without requiring any a-priori knowledge of loads or material properties since only strain-displacement relationships are involved in the calculations.

3. iFEM exploitation for damage identification

The iFEM model \( M_{\text{iFEM}} \) for strain field computation (\( \mathbf{e}_{\text{iFEM}} \)) as a function of \( \mathbf{e}_{\text{in}} \) is used hereafter for the definition of a synthetic index representative of the health state of the structure, then allowing the definition of a load adaptive baseline.

The damage identification procedure assumes a defect alters the strain field of a structure with respect to its normal condition. Consider the strain measures \( \mathbf{e}_{\text{in}} \) passed as input to the iFEM are collected from \( n_{in} \) input sensors at \( \mathbf{x}_{in} \) positions in a damaged component.

If no damage is included in the iFEM mesh geometry, a discrepancy between the measured and reconstructed strain fields will exist, as the iFEM model (\( M_{\text{iFEM}} \)) always reconstructs \( \mathbf{e}_{\text{iFEM}} \) compatible with the geometrical discretization of the structure, which includes no defects. If a pattern of test strain measures, \( \mathbf{e}_{\text{t}} \), collected from \( n_{t} \) test sensors at \( \mathbf{x}_{t} \) positions is available, the structural health state can be inferred by a comparison between the test strain measures \( \mathbf{e}_{\text{t}} \) and the iFEM reconstruction, \( \mathbf{e}_{\text{iFEM}} \), in the same \( \mathbf{x}_{t} \) test positions. Since in most of the engineering problems a plane strain measure is usually possible, allowing the computation of \( \varepsilon_{xx}, \varepsilon_{yy}, \gamma_{xy} \) strain components if a strain rosette is used, an equivalent strain \( \varepsilon_{eq}: \mathbb{R}^3 \rightarrow \mathbb{R}^1 \) is exploited to condensate in a synthetic index all the information available, moving from a comparison in \( \mathbb{R}^3 \) to one in \( \mathbb{R}^1 \). In particular, the equivalent strain is selected proportional to second invariant of the deviatoric strain tensor [23], indicating shape change at constant volume and taking the form:

\[
\varepsilon_{eq} = \sqrt{\frac{1}{2} \left( \left( \varepsilon_{xx} - \varepsilon_{yy} \right)^2 + \varepsilon_{xx}^2 + \varepsilon_{yy}^2 + 6 \gamma_{xy}^2 \right)}
\]
After evaluating $\varepsilon_{eq}$ at $x_t$ positions as a function of $\varepsilon_t$ and $\varepsilon_{iFEM}$, obtaining $\varepsilon_{eq,t} \in \mathbb{R}^{n_t}$ and $\varepsilon_{eq,iFEM} \in \mathbb{R}^{n_t}$ respectively, an anomaly index is computed for each test positions $x_t \subset X_t$ as the percentage difference between $\varepsilon_{eq,t}$ and $\varepsilon_{eq,iFEM}$:

$$i(x_t) = \frac{\varepsilon_{eq,t}(x_t) - \varepsilon_{eq,iFEM}(x_t)}{\varepsilon_{eq,t}(x_t)} \cdot 100$$  \hspace{1cm} (6)

Collecting all the $n_t$ indices defined in eq.(6) in a vector $i(x_t) \in \mathbb{R}^{n_t}$, the structural health state and the possible damage location can be inferred. For an healthy structure, the vector $i(x_t)$ is expected to results in a null vector, $i(x_t) = 0$, meaning a perfect correspondence between $\varepsilon_{eq,t}$, $\varepsilon_t(x_t)$ and $\varepsilon_{eq,iFEM}$, always compatible with the healthy structure, and the measured strain, $\varepsilon_t$, function of the health state.

One main advantage of using $i(x_t)$ for damage identification is that it enables to maintain a constant baseline pattern of anomaly indices $i(x_t)$ regardless of the load or combination of loads acting on the structure, thus adapting in real time the baseline without any requirement for algorithm training.

A schematic representation of the load adaptive baseline working mechanism is shown in Figure 1. Supposing a varying boundary load is applied to the healthy structure at discrete time steps and considering a generic time step $k$, the load condition $l_k$ generates a strain field affecting both the input strain measures $\varepsilon_{in,k}$ and the test measures $\varepsilon_{t,k}$. The former is passed as input to the iFEM model $M_{iFEM}(\varepsilon_{in,k})$, then calculating $\varepsilon_{eq,iFEM,k}$, while the latter is directly used for calculating $\varepsilon_{eq,t,k}$. If the healthy structure is considered, the following identity can be derived $\varepsilon_{eq,iFEM,k} = \varepsilon_{eq,t,k}$, thus $i_k = 0 \forall k \in \mathbb{N}$, independently from the load condition.

However, the latter holds only in a rather ideal situation. Indeed, $i_k = 0$ holds under these hypothesis:

1. The iFEM model represents exactly the structure geometry and boundary conditions.
2. No limitations are posed in the number of inverse elements, $n_{qi}$.
3. All the inverse elements are instrumented with at least a strain rosette measuring three strain tensor components ($\varepsilon_{xx}, \varepsilon_{yy}, \nu_{xy}$).
4. Noise-free input ($\varepsilon_{in,k}$) and test ($\varepsilon_{t,k}$) strain measurements.

Anyway, the hypotheses above are not even remotely met in realistic situations, thus $i_k \neq 0$ holds also for the healthy structure. In this case, one can collect some example patterns of the baseline, e.g. by experiments, thus taking into account a realistic sensor layout, noise and uncertainties, then applying novelty detection schemes for outlier identification.
e.g. based on Mahalanobis distance [24]. As the literature on novelty identification is vast [3], for brevity and without any loss of generality, only the robustness of the feature extraction under different boundary load conditions is demonstrated below.

4. Case study

A numerical verification of the proposed method for anomaly identification is shown for a simple cracked plate subjected to different loading conditions. A description of the reference specimen, the simulated strain patterns for testing the methodology under different load conditions and the iFEM model are briefly described.

4.1 The specimen

A clamped plate subjected to different loading conditions is considered. The plate has a length of 150 mm, a width of 60 mm and a thickness of 2 mm (Figure 2).

![Figure 2: Plate dimensions(mm), boundary conditions and crack position](image)

The plate is made of Aluminum with an elastic modulus of 79 GPa and a Poisson’s ratio of 0.33. Four load conditions are applied at the free end of the plate:

1. Load in the positive X direction, with a magnitude of 60 N, simulating plate tension
2. Load in the negative Z direction, with a magnitude of 60 N, simulating plate bending
3. Torque in the positive X direction, with a magnitude of 120 Nmm
4. A combination of the previous loads: load in the positive X direction and in the negative Z direction (120 N each) and a torque in the positive X direction (120 Nmm)

A 30 mm crack is located in the middle of the plate, as shown in Figure 2.

4.2 The direct FEM for strain measure simulation

The applicability of the damage identification procedure is preliminarily demonstrated with simulated strain measures. Both the strain measures as input to the iFEM ($\varepsilon_{in}$) and the test measures for damage index calculation ($\varepsilon_f$) are numerically simulated by a direct Finite Element model of the plate in Figure 2. The latter, consisting in a high-fidelity mesh composed by 9000 S4 shell elements with a dimension of 1 mm, is created with...
ABAQUS software. Fatigue crack damage is introduced using the SEAM feature available in ABAQUS which duplicates the nodes along the crack edge, allowing the crack opening when the load is applied.

The FE model is used to simulate strain patterns both in healthy and damaged states for the four loading conditions identified above, that will be used to test the method. An example of the strain pattern and the deformed configuration simulated for each loading condition is reported in Figure 3. Though the influence of noise on the anomaly identification results is a mandatory investigation for future implementation of the method due to the intrinsic noisy nature of real strain measures, for brevity, no noise is considered in this work to corrupt the simulated input measures. However, some works are available in the literature verifying the iFEM robustness against noisy measurements [17] due to the intrinsic smoothing operations included in the iFEM procedure, which facilitate an accurate displacement field reconstruction by the algorithm [18].

![Simulated strain field](image)

**Figure 3:** Simulated strain field for different loading conditions; (a) Strain field $\varepsilon_{xx}$ under loading condition 1; (b) Strain field $\varepsilon_{xx}$ under loading condition 2; (c) Strain field $\gamma_{xy}$ under loading condition 3; (d) Strain field $\varepsilon_{xx}$ under loading condition 4

### 4.3 The inverse FEM for strain reconstruction and damage identification

The same plate structure shown in Figure 2 is discretized with a coarse mesh including 360 4-nodes inverse shell elements with 24 degrees of freedom [22] with a dimensions of 5 mm, thus requiring a very low computational effort in view of a future real-time implementation of the method, though without worsening the displacement field reconstruction. Clamp boundary condition is applied by forcing global displacements to zero at the left side of the plate. Since at the beginning of the service life the component can be reasonably assumed to be undamaged, the iFEM model presents no hints of crack presence in the element connectivity, eventually highlighting non-compatibility of $\varepsilon_t$ with the displacement field reconstructed by the iFEM, $\mathbf{U}$, when the real structure is damaged. As anticipated in Section 2, no information on load and material property is passed to the iFEM.
The last pre-processing step requires the definition of the input \( (\mathbf{x}_{\text{in}}) \) and test \( (\mathbf{x}_t) \) strain sensor positions. Two sensor grids are defined for the input \( (\mathbf{e}_{\text{in}}) \) and test \( (\mathbf{e}_t) \) strains (Figure 4). The input grid, including a measure on the top and bottom surfaces at each sensor position \( (x_{\text{in}}) \), is composed by strain rosettes placed at the edges of the plate (Figure 4a). Since, in reality, one is not able to provide each element with a strain measure for economical and practical issues, only some of the inverse elements are instrumented for strain field reconstruction and including a single sensor position, \( n = 1 \), however without hampering the method applicability. Test sensors, consisting again in strain rosettes, are placed in the central part of the plate (Figure 4b), neglecting the regions close to the clamp and the applied load. It has to be noticed that such sensor grids have been selected for the purposes of a general demonstration of the method while, in a generic realistic application, the sensor network must be optimised considering the load and the damage configurations, in order to guarantee the desired damage sensitivity and identification accuracy, which is matter of future research by the authors.

![Figure 4: Strain sensor grids within the plate; (a) Input sensors positions \( (x_{\text{in}}) \); (b) Test sensors positions \( (x_t) \)](image)

5. Results

The damage identification outcomes for the clamped plate described in Section 4.1 and subjected to different loading conditions are presented in this section. Subplots in Figure 5 present the anomaly index results, computed for each test positions, for the different load configurations highlighted in Section 4.1. The peak value (in magnitude) of the anomaly index is also reported in Table 1, for the healthy and damaged conditions and separately for each load configuration.

<table>
<thead>
<tr>
<th>Plate under loading condition number</th>
<th>Anomaly Index magnitude of the healthy structure in % (max)</th>
<th>Anomaly Index magnitude of the cracked structure in % (max)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plate under loading condition number 1</td>
<td>0.9874</td>
<td>203.4418</td>
</tr>
<tr>
<td>Plate under loading condition number 2</td>
<td>3.1042</td>
<td>352.9873</td>
</tr>
<tr>
<td>Plate under loading condition number 3</td>
<td>4.6349</td>
<td>28.8981</td>
</tr>
<tr>
<td>Plate under loading condition number 4</td>
<td>5.7824</td>
<td>394.4001</td>
</tr>
</tbody>
</table>
The baseline error, or the envelope of the anomaly index for the undamaged case, remains close to zero, thus confirming the baseline adaptability to different input load configurations. The maximum value in magnitude of the anomaly index presents a high damage sensitivity, reflected in a significant difference between the damaged and healthy conditions. In particular, if the structure is undamaged, though small errors are introduced by the iFEM when a limited number of input sensors are used for the strain field reconstruction provoking a wider baseline envelope with respect to the ideal condition ($\tilde{f}(x) = 0$), the corresponding maximum value (in magnitude) of the anomaly is still close to zero (e.g. 0.99 % for loading condition 1). On the contrary, if the structure is damaged, it largely differs from zero (e.g. the error raises to 203.5 % for loading condition 1). The former error is mainly related to the limited number of input strain measures, $e_{in}$, and to a coarse iFEM mesh. The latter is due to the iFEM impossibility to reconstruct a displacement field compatible with the test strain measures in the presence of a crack, since the iFEM input model mesh presents no crack.

Furthermore, the closer the position of the anomaly index computation to the crack edge, the lower the anomaly index, indicating the anomaly index distribution can also be exploited for the damage localization. For the loading condition 1, an unexpected sensitivity decrease can be noticed in correspondence of the crack edge (Figure 5a). However, this is not a deficiency of the method but is related to approximations of the direct FEM solution that is used here for simulating sensor measures.

Though the baseline condition remains load independent without training requirements, the anomaly index sensitivity to damage remains dependent on the load configuration. In fact, if in the case of the loading condition 1, 2 and 4 a relatively high sensitivity is found also at a significant distance from the damage, less sensitivity is shown in Figure 5c for the loading condition 3 (i.e. torque). The latter is related to a limited difference of the shear deformations ($\gamma_{xy}$) between the healthy and damage states, as well as to a more local effect of the crack over the strain field, as highlighted in Figure 3c. This fact traduces in Figure 5c in a limited difference in the magnitude of the anomaly indices calculated for the damaged and healthy cases in presence of the load case 3.
6. Conclusions

In this work, a new feature for anomaly identification is defined based on the inverse Finite Element Method. The iFEM ability to reconstruct the strain field of a structure as a function of discrete strain measurements without requiring any a priori knowledge of the applied load and material properties is exploited to define a load adaptive baseline easily implementable in damage identification scenarios. An anomaly index is defined as the percentage difference between an equivalent strain calculated from a strain measure at a test sensor position and the one computed through the iFEM strain reconstruction in the same location. For a properly discretized healthy structure the two equivalent strains will match, generating a pattern of zero valued anomaly indices in the test positions, independently from the applied load configuration. On the contrary, a modification in the real strain field due to a defect will be reflected in a mismatch between the two parameters, leading the anomaly index to largely differ from zero in the test positions close to the damage. The numerical results confirm the validity of the proposed method for anomaly identification. A significant sensitivity to a fatigue crack defect is noticed in a clamped plate subjected to different load configurations, reflected in a significant deviation of the anomaly index from the baseline. Little loss of precision under varying loading condition is shown, with the peak value of the anomaly index always found in the vicinity of the defect, confirming the possibility to exploit the method also for damage localization. Finally, though the results presented in this work are obtained with strain rosette sensors, allowing to pose no limit on the type of load acting on the structure provided a sufficient number of sensors are used as input to the iFEM, in reality one is likely to measure a single strain tensor component due to economic and practical issues, e.g. exploiting distributed strain monitoring by fiber optic technologies. Though not reported here being matter of present and future research by the authors, the method remains valid also if mono-axial strain sensors are used for the strain field reconstruction, implying however a loss of generality with respect to the load independency. However, in most of the engineering problems, the structures present a preferential load transfer capability, thus justifying the measurement of only mono-axial strains. Furthermore, future research by the authors is devoted to the experimental validation of the method, investigating the method robustness against noisy measurements.

References


