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*Review*

# Structural health monitoring and damage assessment Part I: A critical review of approaches and methods

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**Aging and deterioration of existing structures and the need for rapid assessment and evaluation of these structures for hazard mitigation have significantly expanded the research efforts in the field of structural health monitoring (SHM). SHM involves monitoring of a structure using periodically sampled measurements, extraction of damage sensitive features from these measurements, and assessment of the current health state/integrity of the system. Extraction of damage signatures that allows one to distinguish between the undamaged and the damaged structure from the measured vibration response is the area of SHM that receives the most attention. This paper presents a critical review of the damage assessment methodologies based on the research and applications reported in the literature. Challenges and research gaps in SHM are emphasized. These challenges include optimization of the number and location of sensors, identification of features sensitive to small damage levels, ability to discriminate changes in these features caused by damage from those caused by changing environmental or test conditions, and development of statistical methods to discriminate features from structures in undamaged and damaged states. A companion paper presents an application on the vibration data obtained from the ASCE benchmark structure.**

**Key words:** Vibration based structural health monitoring, global methods, damage assessment.

## INTRODUCTION

Structural health monitoring (SHM) is the process of implementing a damage identification strategy for civil infrastructures. Damage identification problem involves detection, localization and assessment of the extent of damage in a structure so that its remaining life can be predicted and possibly extended. SHM encompasses both local and global methods of damage identification. The local methods include visual inspections and non-destructive evaluation tools such as acoustic emission, ultrasonic, magnetic particle inspection, radiography and eddy current. All these techniques, however, require apriori localization of the damaged zone and easy access to the portion of the structure under inspection. As an alternative that overcomes these limitations, global vibration based methods have been widely developed over the years (Farrar et al., 1994; Salawu, 1997; Doebling et al., 1998; Sohn et al., 2003; Chang et al., 2003; Farrar and Worden, 2007). SHM based on vibration measurements involves temporal observation of a structure using periodically sampled vibration measurements, extraction of damage sensitive features from these measurements and assessment of the current health state/integrity of the system. The basic premise of the vibration-based techniques is that the vibration characteristics or the so-called modal parameters (frequencies, mode shapes and modal damping) are functions of the physical properties of the structure (mass, energy dissipation mechanisms and stiffness) and changes in these physical properties cause changes in the modal properties. This postulation, however,

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is compromised by the fact that temperature changes, moisture and other environmental factors also produce changes in dynamic characteristics. If the causes of changes in dynamic characteristics other than damage are considered to be noise in the measurement, then the changes due to damage must be significantly larger than the noise in order for the techniques to work. Usually four different levels of damage identification are studied (Rytter, 1993): damage detection (Level 1), damage localization (Level 2), damage quantification (Level 3), and prediction of the remaining service life of the damaged structure, or the acceptable load level to reach the intended service life (Level 4).

The scope of the paper is limited to the global damage strategies based on measured vibration data, excluding local SHM techniques and damage prognosis. The SHM applications using these strategies reported in the literature are summarized with the emphasis on the challenges and research gaps between the theory and SHM practice.

## DAMAGE IDENTIFICATION APPROACHES

Most of the existing global damage identification methods can be classified into two groups: model-based and non-model or feature-based methods. The model-based methods are essentially model updating procedures in which the mathematical model or the physical parameters of a structure is calibrated or updated using vibration measurements from the physical structure (Zimmerman and Kaouk, 1992; Fritzen et al., 1998). Analytical sensitivities of response parameters to changes in physical properties are used to update modeling assumptions, physical sizing, elastic moduli, etc. The feature-based approaches detect structural changes by detecting damage features in the measured data without the need for an analytical model of the structure. The main task here is the extraction of damage features sensitive to structural changes so that damage can be identified from the measured vibration response of civil engineering structures.

The civil engineering community has been studying the vibration-based damage assessment of bridge and building structures since the early 1980s. The ASCE Benchmark structure of a 4-story 2-bay by 2-bay steel frame scale-model structure built and tested in the Earthquake Engineering Research Laboratory at the University of British Columbia, Canada (Dyke et al., 2003); the 2-story 8 by 9 m building structure of the STEELQUAKE project constructed and tested at the European Laboratory for Structural Assessment (ELSA) at the Joint Research Centre (JRC) at Ispra, Italy; the Z24 prestressed bridge, with three spans, two lanes and 60 m overall length of the SIMCES project in Switzerland (Worden, 2003); and the ANCRISST structural health monitoring problem of a cable-stayed bridge constructed in mainland China comprising a main span of 260 m and two side spans of 25.15+99.85 m each (http://smc.hit.edu.cn) can be listed among major research initiatives in this field.

Both model-based and non-model based approaches utilizing the measured data in time-domain, frequency domain or modal domain were investigated. While measurements were always performed in the time domain, data could be analyzed in any of the three domains. Although conversion between domains involves some data compression, Friswell and Penny (1997) argued that loss of information during conversion was minimal for linear systems and that the frequency domain may be more advantageous in reducing the effects of random noise. Modal domain introduces further reduction of the measured data since only the modes within a frequency band are considered. Friswell and Penny (1997) find this acceptable unless the out of band modes are very close, that is, the response is dominated by the in-band modes. Lee and Shin (2002) disagree with this argument pointing out the fact that the modal data can be contaminated by modal extraction error which the frequency response function data does not possess.

## FEATURE-BASED METHODS

The following methods were proposed in the literature for feature-based damage detection in civil engineering structures (Doebling et al., 1996; Sohn et al., 2003; Randall et al., 2004a, b):

1. Natural frequency based metrics.
2. Mode shape based metrics.
3. Structural damping based metrics.
4. Modal strain energy based metrics.
5. Flexibility based methods and other matrix perturbation approaches.
6. Pattern Recognition, neural networks and other statistical approaches.
7. Non-linear methods based on advanced time-variant transforms.
8. Other methods.

### Natural frequency based metrics

Damage detection based on changes or shifts in natural frequency has been the topic of numerous research studies (Salawu, 1997). These studies have revealed that changes in frequencies alone may not provide enough information for damage detection, especially in the case of large structures, for the following reasons:

(a) Damage is a local phenomenon and may not significantly influence the global low-frequency response behavior of structures typically measured during vibration

tests. Hence, high damage levels are often required for noticeable frequency shifts (Doebling et al., 1998; Salawu, 1997; Sohn et al., 2003). Tests on the I-40 Bridge conducted by Farrar et al. (1994) showed that a 96.4% reduction in the cross-sectional stiffness at the center of a main plate girder causing a 21% reduction in the bending stiffness of the overall bridge cross-section resulted in no significant reductions in the modal frequencies. The first four fundamental frequencies of a steel channel studied by Chen et al. (2005) exhibited no shifts greater than 5% due to a single notch severe enough to cause the channel to fail at its design load.
(b) The spatial wavelengths of the low-frequency modes are typically far larger than the extent of damage, which makes its detection difficult.
(c) Structures usually behave in a (weakly) nonlinear and time-varying fashion, which reduces the effectiveness of the approaches that are based on linear system modeling.
(d) Dynamic characteristics of structures, especially bridges, can be significantly affected by the environmental temperature.
(e) Data measured from actual structures are inevitably contaminated by noise. The distinction between damage and noise may be fuzzy.
(f) Different damage cases may provide similar frequency-change characteristics. In case of symmetric structures, for instance, the change in natural frequency due to damage at two symmetric locations is exactly the same.
(g) The identification of multiple damage scenarios using frequency shifts is a challenge even for simple laboratory structures.
(h) If a member is not strained in its fundamental mode, loss of that member has no effect on the fundamental frequency.
(i) In reinforced concrete structures where most of the stiffness is provided by the concrete, deterioration of the reinforcing steel was shown to have little influence on the natural frequency of the structure (Friswell and Penny, 1997).
(j) In highly redundant structures such as shells, damage in the form of a notch does not produce measurable changes in the dynamic characteristics of the structure (Srinivasan and Kot, 1992).
(k) Some forms of damage such as the loss of a bolt in the connection with several bolts may not affect the frequency at low levels of vibration (Chang et al., 2003).
(l) Chen et al. (2005) investigated steel space structures subjected to atmospheric corrosion and showed that the atmospheric corrosion does not lead to a perceptible change in the natural frequencies of the structure.

The success of the algorithms using frequency shifts for detecting damage is generally limited to small laboratory structures with a single or a few damage locations. The use of frequency changes alone for identifying damage in applications to full-scale structures does not seem promising with the exception of the work done by De Roeck et al. (2000). Following a progressive damage-testing program on the Z24 Bridge in Switzerland, the effects of air temperature, humidity, rain, wind speed and wind direction were monitored through hourly readings from 16 accelerometers placed on the bridge. It was demonstrated that once the effects of environmental influences were filtered out, stiffness changes could be detected if the corresponding frequency shifts were more than 1%.

## Mode shape based metrics

In formulating the eigenvalue problem, assuming that structural damage only affects the stiffness matrix and not the mass matrix, the undamaged and damaged conditions of a structure can be represented by the following expressions, respectively:

$$([K]-\lambda_i[M])\{\phi_i\}=0 \quad (1)$$

$$([K^*]-\lambda_i^*[M])\{\phi_i^*\}=0 \quad (2)$$

where $[K]$ and $[M]$ are the stiffness and the mass matrices, $\lambda_i$ and $\phi_i$ are the *i*th eigenvalue and eigenvector corresponding to the undamaged condition, respectively, and the asterisk denotes the damaged condition. The pre- and post-damage eigenvectors are used as the basis for damage detection (Law et al., 1998; Shi et al., 2000a; Hu et al., 2001; Siringoringo and Fujino, 2008).

Mode shape curvatures which can be estimated numerically from derivatives of the displacement mode shapes have also been used for damage detection purposes. The use of mode shape curvatures in damage identification is based on the assumption that the changes in the curvatures of mode shapes are highly localized to the region of damage and that they are more pronounced than changes in the displacement mode shapes. Alampalli et al. (1997), however, showed that this is not necessarily the case, particularly for structures with redundancy since the curvature is often calculated from the measured displacement mode shapes using a central difference approximation. The challenges associated with mode shape based methods can be summarized as follows:

(a) Mode shape based methods generally require measurements at many locations on the structure, which requires a dense sensor resolution.
(b) No changes in a mode shape can be detected if the mode has a node point at the location of damage.
(c) These methods require data with high signal to noise ratio and although they are well verified with simulated data, noise and measurement errors, which are inevitable,

can be major drawbacks in practical applications.
(d) These methods require an accurate and a well correlated model of the structure.
(e) Environmental effects have to be monitored and changes due to environmental conditions need to be distinguished from changes due to damage.

Studies by Kim and Stubbs (1995), Salawu and Williams (1995) and Shi et al. (2000a) suggest that methods based on mode shapes are more robust than those based on natural frequency shifts. While Ren and De Roeck (2002) cast doubts on the use of mode shapes for damage detection in large structures, Wahab and De Roeck (1999) presented promising results from a bridge application.

## Structural damping based metrics

Damping properties have seldom been used for damage detection due to the high errors involved in estimating damping values and the existence of various definitions of damping. A review of the existing literature, however, suggests that crack detection in a structure based on damping may prove to be more advantageous than detection schemes based on frequency and mode shapes. The study by Modena et al. (1999) on identification of manufacturing defects causing structural damage in precast members revealed that visually undetectable cracks cause very little change in resonant frequencies and require higher mode shapes to be detected, while the same cracks cause larger changes in damping. Kawiecki (2000) suggests that damping as a damage-sensitive indicator can be useful for especially lightweight structures and microstructures. Zonta et al. (2000) showed that cracking of prestressed reinforced concrete hollow panels produces a frequency splitting in the frequency domain and the beat phenomenon of the free decay signals in time domain. It is claimed that the crack formation in prestressed concrete causes a non viscous dissipative mechanism, making damping more sensitive to damage. Curadelli et al. (2008) developed a damage detection strategy with the instantaneous damping coefficients identified using wavelet transforms. The experimental results obtained from a simply supported reinforced concrete beam and a one-bay six story aluminum frame suggest that damping reveals more marked variations than frequency upon damage.

The limitations of using damping properties for damage detection can be listed as follows:

(a) Consistent measurement and accurate modeling of damping is difficult. Alampalli et al. (1997) and Farrar and Doebling (1999) reported large scatter in the measured damping values from laboratory tests.
(b) For low frequency modes that also have low damping, such as the case for long suspension bridges, damping ratios are overestimated due to bias errors. Littler (1992) reported a 25% increase in the damping ratio of a long span suspension bridge when measurement duration was reduced to 1 h from 13 h. He also showed that there was a pronounced increase in damping value with increasing wind speed.
(c) Even when the damping values are measured with a high level of accuracy, the observed changes may not give any indication of damage. Casas and Aparicio (1994) investigated the identification of cracking in laboratory size concrete beams. Using a model updating technique, it was found that damping was not significantly different in the cracked beams compared to the uncracked beams and that there was no clear relation between crack growth and increase in damping.

## Modal strain energy based metrics

The change in the strain energy stored in a particular vibration mode is also investigated as a potential indicator of damage. Kim and Stubbs (1995) developed a damage indicator based on the ratio of modal strain energy of elements before and after damage and applied this algorithm to locate and size a single crack in an experimental plate girder. Stubbs and Kim (1996) used the same indicator to localize and estimate severity of damage in an experimental two-span beam. Farrar and Doebling (1999) also used the same damage index for locating controlled damage in a bridge and found that this method outperformed the direct comparison of the mode shape curvature before and after damage. Park et al. (2001) applied a modal strain energy method to a laboratory space truss with 300 elements. In 17 damage scenarios, 16 of the 22 truly damaged members were identified. Law et al. (1998) developed a modal strain energy based method that is applied successfully to an experimental two-storey plane frame for which damage was simulated with loose joints. Hu et al. (2001) developed a damage assessment methodology using modal strain energy tailored to single damage cases and demonstrated the performance of the developed method on an experimental fixed-fixed beam with a single saw cut. Shi et al. (2000b) were able to locate the loosening of up to two semi rigid bolted joints in an experimental steel frame by calculating the change in the modal strain energy. Peterson et al. (2001a, b) applied a modal strain energy method to locate a saw cut damage in a laboratory timber beam. As the depth of the cut increased, the confidence in the correct localization of damage increased. Cornwell et al. (1999) extended the 1-D strain method to 2-D and applied both methods to an experimental aluminum plate with two saw cuts. Both methods exhibited a tendency to produce false-positive results especially at low levels of damage. Kim et al. (2003) applied both a frequency based and a modal strain energy based method to locate damage in a simulated beam. The modal strain energy method was found to produce more accurate predictions than the frequency based method. Shi et al. (2000b) stated that modal expansion may be required to successfully locate damage and found that modal truncation error may lead to errors in quantification of damage. Similar to above-mentioned methods, masking effect of noise may have a pronounced effect in the low damage scenarios.

### Flexibility based methods

The dynamically measured flexibility matrix, $[\boldsymbol{F}]$, is estimated from:

$$[F]=[\Phi][\Lambda]^{-1}[\Phi]^{T} \tag{3}$$

where $[\Phi]$ is the measured mode-shape matrix, $[\Lambda]$ is the diagonal matrix of the associated measured modal frequencies squared and $T$ denotes the transpose operation. A truncated version of the flexibility matrix is generally estimated using only the lower vibration modes due to practical difficulties in measuring the higher modes. The flexibility matrix is most sensitive to changes in the lower frequency modes because of the inverse relationship to the square of the modal frequencies.

Pandey and Biswas (1994) and Li et al. (1999) used the change in flexibility as a damage feature. Bernal (2002) and Bernal and Gunes (2004) developed the Damage Locating Vector (DLV) approach mapping changes in flexibility to the spatial distribution of damage. The principle behind the method is the fact that the null space of the change in flexibility provides vectors that, when treated as loads on the structure, lead to stress fields that are zero over the damaged portion of the domain. An appreciation of why this is so can be gained by noting that the null space of the change in flexibility contains vectors that lead to identical displacements (at the sensors) in the undamaged and damaged states. The DLV localization is in principle carried out by computing the null space of the change in the flexibility matrix upon damage, treating the computed vectors as static loads on the system and identifying the damage as the intersection of the regions of zero stress. The application of the DLV method to the IASC-ASCE structural health monitoring benchmark structure is presented in the companion paper (Gunes and Gunes, 2012). Zhang and Aktan (1995) used the change in curvature (second derivative) of the flexibility matrix at the pre- and post-damage states to determine the location of damage.

Zhao and DeWolf (1999) examined and compared sensitivity coefficients for natural frequencies, mode shapes and modal flexibility. Application to a simulated five DOF spring mass system revealed that the modal flexibility was most sensitive to damage. Farrar and Doebling (1999) compared strain energy, mode shape curvature and the flexibility based methods for locating damage on the I-40 Bridge over the Rio Grande in America. Four controlled damage states were investigated and it was found that the strain energy based method was the most successful one followed by the mode shape curvature based method. In this study, the change in flexibility method could only locate damage in the most severe damage scenario.

### Pattern recognition, neural networks and other statistical approaches

The inherent uncertainties in the measured data are recognized as one of the main barriers against the application of vibration based damage detection techniques on real life structures. Farrar and Doebling (1999) suggested that the vibration based damage detection problem is fundamentally one of statistical pattern recognition and that any advancement in the state of the art requires the developments of non-model based pattern recognition methods supplement the existing model based techniques. The objective of pattern recognition in damage detection is to distinguish between different classes of patterns representing damage conditions. Statistical pattern recognition assigns features to different classes using statistical density functions. In recent years, neural networks have been established as a powerful tool for pattern recognition (Mangal et al., 1996; Waszczyszyn and Ziemianski, 2001; Zubaybi et al., 2002). The architecture and the training process of neural networks depend on the required level of damage identification. An unsupervised scheme offers the possibility of novelty detection. Novelty detection is concerned with the identification of any deviations in measured data relative to data measured under normal operating conditions. Features derived from measurements taken from a structure in its undamaged state will have a distribution with an associated mean and variance. If the structure is damaged, then there may be a change in the mean, the variance, or both. A supervised learning scheme is required for determining location and severity of damage. This scheme, however, usually needs a correlated numerical model of the structure for localizing and quantifying the damage.

The main challenge associated with pattern recognition approaches is that they require significant amount of pre-processing. In the case of neural network approaches, pre-processing is needed to extract features for training. Pattern recognition analysis requires feature selection procedures for training. Some advanced pattern recognition approaches require a large number of features, and as the dimensionality of the feature space increases, the design of a good classifier becomes more difficult. Reduction of dimensionality then becomes a major challenge in pattern recognition. Novelty detection schemes provide information only on the existence of damage; however, they do not require any models of damage. They are also suitable for data sets obtained through ambient excitation only, for example traffic or wind loading on a bridge structure (Siringoringo and Fujino, 2008; Zhang et al., 2009).

Statistical process control provides a framework for monitoring the distribution of the features and identifying new data that is inconsistent with the previous data. If all other variables can be eliminated, then a change in the distribution characteristics of the features will indicate damage. Worden et al. (2000), Fugate et al. (2000) and Carden and Fanning (2004) all considered statistical process control approaches for damage detection. Four waveform recognition techniques to distinguish between frequency response function (FRF) waveforms of intact and damaged bridges were investigated by Samman and Biswas (1994a, b) in two companion papers. INRIA in France recently proposed a statistical model based damage detection and localization method utilizing a subspace based residual and a statistical analysis of aggregated sensitivities of the residual to damage (Basseville, 2002). A disadvantage of these methods is that they are generally limited to Level 1 or possibly Level 2 identification. Hence, the detection of damage, rather than location and quantification, is the objective of using statistical pattern recognition. Ching and Beck (2004) devised a statistical Bayesian updating methodology based on expectation–maximization algorithm that can find the most probable values of the parameter with their probability density functions and applied the approach to the ASCE benchmark structure. Although the approach was found to be reliable in detecting the local damage in the bracing system, the connection is found to be much more difficult to detect.

### Non-linear methods based on advanced time-variant transform

The use of linear and non-linear functions and transforms of data is a common way of feature reduction procedure for damage identification. There exist a number of methods based on Fourier analysis. The majority of these methods are based on the assumption that the analyzed data is linear and stationary. Many damage mechanisms such as cracks, however, will produce non-linear effects. Assuming the rest of the structure is linear, there is a very local non-linearity in a predominantly linear structure. Thus it is probable that the small changes due to damage may be more identifiable if the non-linear effects can be separated from the linear effects. Methods using wavelets and other time frequency transformations such as Hilbert-Huang transform and Wigner-Ville distribution show promise due to their ability to examine local data with a zoom effect. The zoom effect can provide multi levels of details and approximations of the original signal (Liew and Wang, 1998; Hou et al., 2000; Yang et al., 2004; Hera and Hou, 2004). Damage and the moment when the damage occurs can be detected by a spike in the time-frequency plot. The spatial distribution of spikes may be used to identify the location of damage.

### Other methods

In the literature, there are also techniques that do not fall into any of the categories described above. Sawyer (2000) proposed a fuzzy logic based damage identification system. Sohn and Law (2001) made use of Ritz vectors extracted from measured flexibility. Tan et al. (2001) studied dynamic response of reinforced concrete slabs and showed that plots of measured dynamic strain display unique deflection signatures that varied with the internal state of the slab.

## MODEL UPDATING BASED METHODS

Model-based also called parametric methods are based on a model of the structure, some parameters of which are adjusted using vibration measurements, by minimizing the difference between the parameters computed with the model and the ones that are derived from the measurements (Mottershead and Friswell, 1993; Friswell and Mottershead, 1995). Damage, in this context, is viewed as shifting of values in a set of system parameters and damage characterization falls in the realm of model updating as an optimization problem. This optimization problem is often non-convex which may totally miss the real optimum leading to wrong parametric values. Global iterative optimization methods exist to solve this problem, such as coupled local minimizers, genetic algorithms, or simulated annealing. Furthermore, the quality of damage location assessment is critically dependent on the detail and accuracy of the structure's finite element model. It is inevitable that there will be errors even in the model of the undamaged structure. This 'systematic error' problem may be reduced and a reliable model may be produced by updating the model of the undamaged structure using data measured from the undamaged structure. Another alternative that eliminate the systematic errors is to use differences between the damaged and undamaged response data in the damage location algorithm. In either case, however, a fundamental difficulty lies in the fact that the inverse problem posed is typically ill-conditioned and, given the constraints imposed by the available data, generally non-unique (Udwadia 1985). Berman (1989) concluded that there can be no unique corrected dynamic model of a structure as long as the model has fewer degrees-of-freedom (DOF) than the actual structure. He argued that as the true actual structure has an infinite number of DOF, there exist an infinite number of physically reasonable models, which adequately predict the behavior of the structure over an adequate frequency range. When such a model is applied to damage determination, the true changes in the physical characteristics are required and this represents a far more onerous task than the prediction of model behavior. In the same vein, Baruch (1978) showed that simultaneous changes in the mass and stiffness matrices could not be identified using modal data alone since the mode shapes could not provide a reference basis. Methods that do use mode shapes as a reference basis may determine the stiffness and mass matrices with significant errors since the solution is non-unique.

The model-updating problems are usually solved by iterative methods that require the solution of the analytical problem at least once in each iteration; hence, its application to large models can be very processor intensive. Although the technological advances in speed and memory of computers allow tackling larger and more complex models than ever before, model size is still an issue. Moller and Friberg (1998) proposed a method that reduced the problem by projection onto a subspace spanned by a reduced number of modes leading to substantial computational time savings. Law et al. (2001) presented a damage detection oriented modeling methodology for large structures. To reduce the number of DOFs, super elements were formulated while the modal sensitivities to small physical changes were maintained for use in a sensitivity based updating algorithm. The method was demonstrated on a simulated bridge deck structure where the initial 5370 DOFs were reduced to 211 DOFs with reasonable success.

Updating techniques arrive at the damaged system properties using constrained optimization algorithms that select a particular solution from the set of possible ones. For example, strategies that use matrix perturbations of minimum rank or minimum norm have been widely used (Baruch, 1978; Kabe, 1985). The minimum norm type solutions generally tend to spread the identified damage over a large number of parameters. The physical parameters obtained from these formulations may be unrelated to the actual damage scenarios, although they are consistent with the measured modal data. Using engineering judgment, such as specifying the likely location and form of damage, are key aspects for the success of any model updating project. An alternative approach that reduces the size of the original updating problem is a multivariate regression method that combines a parameter subset selection process (Lallement and Piranda, 1990; Friswell et al., 1997; Titurus et al., 2003), with a damage function (Teughels et al., 2002; Teughels and De Roeck, 2004).

## CONCLUSION

Structural damage detection and integrity assessment is the fundamental objective of structural health monitoring. A review of the state of the art in vibration based condition monitoring revealed numerous algorithms that use data in time, frequency and modal domains. Many of the algorithms suggested for damage localization are tested on simulated data or on very controlled experimental data. Although simulations are necessary to test the performance of algorithms for various damage cases, they are not sufficient. Laboratory testing is required to simulate the errors that might be expected in real structures. Most identification schemes are able to cope well with the random noise that is often added to simulated data, but not with systematic type errors that exist between the model and the structure.

The monitoring methods used for civil engineering structures mainly rely on linear models due to complex nature of these structures. Material non-linearity or cracking and other damage mechanisms producing non-linear effects which are often ignored can cause problems in damage identification using linear assumptions. Non stationarity of the structure is another significant problem that must be dealt with since environmental effects such as temperature can change the signals from an undamaged structure significantly. Methods based on novelty detection may prove to be advantageous since they do not require any baseline data. However, these methods provide only Level 1 or 2 damage identification.

Despite the extensive research and progress in SHM of structures, global monitoring methods based on dynamic characteristics are unlikely to have an inherent capability for damage location and quantification of operational civil structures in the short term unless the damage to the structure is substantial. Local monitoring techniques are much more likely to locate and quantify the damage. However, since local monitoring of all infrastructures in a timely manner is not a realistic goal at present, global methods should be combined with the use of local monitoring techniques to obtain a better picture of the structural damage.

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