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Summary Review of Vibration-Based Damage Identification Methods

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A SUMMARY REVIEW OF VIBRATION-BASED DAMAGE IDENTIFICATION METHODS

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ABSTRACT

This paper provides an overview of methods to detect, locate, and characterize damage in structural and mechanical systems by examining changes in measured vibration response. Research in vibration-based damage identification has been rapidly expanding over the last few years. The basic idea behind this technology is that modal parameters (notably frequencies, mode shapes, and modal damping) are functions of the physical properties of the structure (mass, damping, and stiffness). Therefore, changes in the physical properties will cause detectable changes in the modal properties. The motivation for the development of this technology is presented. The methods are categorized according to various criteria such as the level of damage detection provided, model-based vs. non-model-based methods and linear vs. nonlinear methods. The methods are also described in general terms including difficulties associated with their implementation and their fidelity. Past, current and future-planned applications of this technology to actual engineering systems are summarized. The paper concludes with a discussion of critical issues for future research in the area of vibration-based damage identification.

INTRODUCTION

The interest in the ability to monitor a structure and detect damage at the earliest possible stage is pervasive throughout the civil, mechanical, and aerospace engineering communities. For the purposes of this paper, damage is defined as changes introduced into a system, either intentional or unintentional, which adversely effect the current or future performance of that system. These systems can be either natural or man-made. As an example, an anti-aircraft missile is typically fired to intentionally introduce damage that will immediately alter the flight characteristics of the target aircraft. Biological systems can be unintentionally subject to the damaging effects of ionizing radiation. However, depending on the levels of exposure, these systems may not show the adverse effects of this damaging event for many years or even future generations. Implicit in this definition of damage is that the concept of damage is not meaningful without a comparison between two different states of the system, one of which is assumed to represent the initial, and often undamaged, state.

Most currently used damage identification methods are included in one of the following categories: visual or localized experimental methods such as acoustic or ultrasonic methods, magnetic field methods, radiography, eddy-current methods or thermal field methods (Doherty, 1997). All of these experimental techniques require that the vicinity of the damage is known *a* *priori* and that the portion of the structure being inspected is readily accessible. The need for quantitative global damage detection methods that can be applied to complex structures has led to the development and continued research of methods that examine changes in the vibration characteristics of the structure.

The increase in research activity regarding vibration-based damage detection is the result of the coupling between many factors. These factors can be generally categorized as spectacular failures resulting in loss of life that have received ample news media coverage, economic concerns, and recent technical advancements. Failures such as the in-flight loss of the exterior skin on an Aloha Airlines flight in Hawaii and the resulting media coverage focus the public's attention on the need for testing, monitoring, and evaluation to ensure the safety of structures and mechanical systems used by the public. The public's concerns, in turn, focus the attention of politicians on this issue and, hence, industry and regulatory agencies are influenced to provide the funding resources necessary for the development and advancement of this technology. The current state of aging infrastructure and the economics associated with its repair have also been motivating factors for the development of methods that can be used to detect the onset of damage or deterioration at the earliest possible stage. Finally, technological advancements including increases in cost-effective computing memory and speed, advances in sensors including non-contact and remotely monitored sensors and adaptation and advancements of the finite element method represent technical developments that have contributed to recent improvements in vibration-based damage detection. Additional factors that have contributed to these improvements are the adaptation and advancements in experimental techniques such as modal testing (most recently by the civil engineering community), and development of linear and nonlinear system identification methods. Recently, a workshop specific to the topic of vibration based health monitoring was held at Stanford University (Chang, 1997).

It is the authors' speculation that damage or fault detection, as determined by changes in the dynamic properties or response of systems, has been practiced in a qualitative manner, using acoustic techniques, since modern man has used tools. More recently, this subject has received considerable attention in the technical literature where there has been a concerted effort to develop a firmer mathematical and physical foundation for this technology. However, the basic idea remains that commonly measured modal parameters (notably frequencies, mode shapes, and modal damping) are functions of the physical properties of the structure (mass, damping, and stiffness). Therefore, changes in the physical properties, such as reductions in stiffness resulting from the onset of cracks or loosening of a connection, will cause detectable changes in these modal properties. Because changes in modal properties or properties derived from these quantities are being used as indicators of damage, the process of vibration-based damage detection eventually reduces to some form of a pattern recognition problem.

The idea that changes in vibration characteristics can provide information regarding damage in a structure is very intuitive and one may ask the question: Why has this technology taken such a long time to be formally and generally adopted by the modern engineering community? The answer is that there are several confounding factors making vibration-based damage identification difficult to implement in practice. First, standard modal properties represent a form of data compression. Modal properties are estimated experimentally from measured response-time histories. A typical time-history may have 1024 data points, and if measurements are made at 100 points, there are 102,400 pieces of information regarding the current state of the structure. For this discussion the additional data typically obtained from averaging will not be considered as providing supplemental data, but rather improving the accuracy of 100 measurements. Through system identification procedures commonly referred to as experimental modal analysis (Ewins, 1984) this volume of data is reduced to some number of resonant frequencies, mode shapes and modal damping values. This data compression is done because the modal quantities are easier to visualize, physically interpret, and interpret in terms of standard mathematical modeling of vibrating systems than are the actual time-history measurements. If twenty real modes are identified, then the 102,400 pieces of information will have been reduced to 2020-2040 pieces of information (20 modes each consisting of 1 resonant frequency value, 1 modal damping value and 100 modal amplitude values).

Intuitively, information about the current state of the structure must be lost in this data reduction and system identification process. The loss of information occurs primarily from the fact that for a linear system the modal properties are independent of the excitation signal characteristics (amplitude and frequency content) and the location of the excitation, whereas the time histories are not. In addition, if the input excites response at frequencies greater than those that can be resolved with the specified data sampling parameters, the identified modes will not provide any information regarding the higher frequency response characteristics of the structure that are contributing to the measured time-history responses. Within the measured frequency range of response it is often difficult to identify all the modes contributing to the measured response because of coupling between the modes that are closely spaced in frequency. This difficulty is observed more commonly at the higher frequency portions of the spectrum where the modal density is typically greater. Also, the introduction of bias (or systematic) errors, such as those that arise from windowing of the data, finite frequency resolution, and those that arise from changing environmental conditions during the test, will tend to make the identified modal parameters less representative of the true dynamic properties of the structure.

Another confounding factor is the fact that damage typically is a local phenomenon. Local response is captured by higher frequency modes whereas lower frequency modes tend to capture the global response of the structure and are less sensitive to local changes in a structure. From a testing standpoint it is more difficult to excite the higher frequency response of a structure, as more energy is required to produce measurable response at these higher frequencies than at the lower frequencies. These factors coupled with the loss of information resulting from the necessary reduction of time-history measurements to modal properties add difficulties to the process of vibration-based damage identification. These factors also contribute to the limitation of this technology to the research arena with only limited practice by the engineering community.

A logical question then is why not examine the time-histories directly for indications of damage? The answer is that, despite the difficulties associated with damage detection based on changes in modal properties, it is even more difficult to identify damage by examining response-time histories directly. To identify that damage has occurred based on the changes in patterns of these time histories and relate these changes to physical changes in the structure is a very difficult problem. If excitation sources change and/or environmental conditions change this process becomes even more difficult. However, it should be pointed out that in a situation where the system response changes from linear to nonlinear, time histories alone (actually their frequency domain power spectra) could be sufficient to identify damage. Generally, correct identification requires that the location of the damage be known *a priori*, as is typically the case with loosening of bearings on rotating machinery. Detecting the onset of nonlinear vibration behavior in rotating machinery represents one of the most widely practiced forms of vibration-based damage identification (Wowk, 1991).

Notwithstanding the difficulties discussed above, advances in vibration-based damage detection over the last 20-30 years have produced new methods of examining dynamic data for indications of structural damage. These methods are seeing more widespread applications. One of the most prominent examples of this application is NASA’s space shuttle modal inspection system (Hunt, et al., 1990). Because of difficulties accessing the exterior surface caused by the thermal protective system, a vibration-based damage detection system was developed. This system has identified damage that would have eluded traditional non-destructive testing methods because of inaccessibility to the damaged components and has been adopted as a standard inspection tool for the Space Shuttle Orbiter structures.

It is the intent of this paper to provide an overview of these recent advances in vibration-based damage detection. This paper is based on a previous detailed review of the vibration-based damage detection literature (Doebling, et al., 1996a). As mentioned previously, the field of damage identification is very broad and encompasses both local and global methods. This paper will be limited to global methods that are used to infer damage from changes in vibration characteristics of the structure. Many different issues are critical to the success of using the observed changes in mechanical vibration characteristics of a structure for damage identification and health monitoring. Among the important issues are excitation and measurement considerations, including the selection of the type and location of sensors, and the type and location of the excitations. Another important topic is signal processing, which includes such methods as Fourier analysis, time-frequency analysis and wavelet analysis. In this paper, these peripheral issues will not be directly addressed. The scope of this paper will be limited to the methods that use changes in modal properties (i.e. modal frequencies, modal damping ratios, and mode shapes) to infer changes in mechanical properties, and the application of these methods to engineering problems. The review includes both methods that are based solely on changes in the measured data as well as those methods that use a finite element model (FEM) in the formulation. The reader should note that methods based on identifying nonlinear response or non-parametric models (such as neural network-based approaches) are not included in this review. Also the large amount of literature applicable to fault detection and diagnosis in rotating machinery is not reviewed. Application-specific experimental considerations are also not included within the scope of this paper.

CLASSIFICATION OF DAMAGE AND DAMAGE IDENTIFICATION METHODS

The effects of damage on a structure can be classified as linear or nonlinear. A linear damage situation is defined as the case when the initially linear-elastic structure remains linear-elastic after damage. The changes in modal properties are a result of changes in the geometry and/or the material properties of the structure, but the structural response can still be modeled using linear equations of motion. Linear methods can be further classified as model-based and non-model-based. Model-based methods assume that the monitored structure responds in some predetermined manner that can be accurately discretized by finite element analysis, such as the response described by Euler-Bernoulli beam theory.

Nonlinear damage is defined as the case when the initially linear-elastic structure behaves in a nonlinear manner after the damage has been introduced. One example of nonlinear damage is the formation of a fatigue crack that subsequently opens and closes under the normal operating vibration environment. Other examples include loose connections that rattle and nonlinear material behavior such as that exhibited by polymers. The majority of the studies reported in the technical literature address only the problem of linear damage detection.

Another classification system for damage-identification methods defines four levels of damage identification, as follows (Rytter, 1993):

- Level 1: Determination that damage is present in the structure
- Level 2: Level 1 plus determination of the geometric location of the damage
- Level 3: Level 2 plus quantification of the severity of the damage
- Level 4: Level 3 plus prediction of the remaining service life of the structure

To date, vibration-based damage identification methods that do not make use of some structural model primarily provide Level 1 and Level 2 damage identification. When vibration-based methods are coupled with a structural model, Level 3 damage identification can be obtained in some cases. Level 4 prediction is generally associated with the fields of fracture mechanics, fatigue-life analysis, or structural design assessment and, as such, is not addressed in this paper.

Another category of classification for damage identification techniques makes the distinction between methods that are used for continuous monitoring of structural performance and methods that are applicable to the detection of damage caused by extreme events. As an example, a system that uses continuous or intermittent accelerometer measurements from sensors mounted permanently to a bridge is different in terms of instrumentation and data acquisition requirements from a system that does not acquire data except during and immediately following an earthquake or a hurricane. It should be noted that the primary distinction between these situations has to do with the sensors and data acquisition system requirements. Typically, the same types of analytical techniques can be applied to the data to determine the integrity of the structure.

EARLY DIFFICULTIES

Most of the modern developments in vibration-based damage detection stem from studies performed in the 1970s and early 1980s by the offshore oil industry. See Vandiver (1975, 1977); Begg, et al. (1976); Loland and Dodds (1976); Wojnarowski (1977); Coppolino and Rubin (1980); Duggan et al. (1980); Kenley and Dodds (1980); Crohas and Lepert (1982); Nataraja (1983); and Whittome and Dodds (1983) for details on these studies. However, most of the proposed techniques were less than successful. Instead, it was found that above-water-line measurements could provide information about resonant frequencies only. Environmental conditions such as marine growth that added significant mass to the structure, equipment noise, and changing mass associated with changing fluid tank levels caused changes in the measurements that were not the result of damage. These tests also identified uniqueness issues associated with locating the damage spatially if only resonant frequencies are used. Because of the lack of success, the oil industry mostly abandoned pursuit of this technology in the mid-1980s.

DAMAGE DETECTION BASED ON CHANGES IN BASIC MODAL PROPERTIES

Numerous other investigators who have tried to examine changes in basic modal properties have encountered issues similar to those encountered in the offshore oil industry. In this context basic modal properties will be defined as resonant frequencies, modal damping, and mode shape vectors.

FREQUENCY CHANGES

The amount of literature related to damage detection using shifts in resonant frequencies is quite large. Salawu (1997a) presents an excellent review on the use of modal frequency changes for damage diagnostics. The observation that changes in structural properties cause changes in vibration frequencies was the impetus for using modal methods for damage identification and health monitoring. Because of the large amount of literature, not all papers that the authors have reviewed on this subject are included in the reference list of this paper. A more thorough review and reference list can be found in Doebling (1996a). An effort has been made to include the early work on the subject, some papers representative of the different types of work done in this area, and papers that are considered by the authors to be significant contributions in this area.

It should be noted that frequency shifts have significant practical limitations for applications to the types of structures considered in this review, although ongoing and future work may help resolve these difficulties. The somewhat low sensitivity of frequency shifts to damage requires either very precise measurements or large levels of damage. However, recent studies have shown that resonant frequencies have much less statistical variation from random error sources than other modal parameters (Farrar, et al. (1997), Doebling, et al. (1997a)).

For example, in offshore platforms damage-induced frequency shifts are difficult to distinguish from shifts resulting from increased mass from marine growth. Tests conducted on the Interstate 40 highway bridge (Farrar, et al., 1994) also demonstrate that frequency shifts are not sensitive indicators of damage. When the cross-sectional stiffness at the center of a main plate girder had been reduced 96.4%, reducing the bending stiffness of the overall bridge cross-section by 21%, no significant reductions in the modal frequencies were observed. Currently, using frequency shifts to detect damage appears to be more practical in applications where such shifts can be measured very precisely in a controlled environment, such as for quality control in manufacturing. As an example, a method known as “resonant ultrasound spectroscopy”, which uses homodyne detectors to make precise sine-sweep frequency measurements, has been used successfully to determine out-of-roundness of ball bearings (Migliori, et al., 1993).

Also, because modal frequencies are a global property of the structure, it is not clear that shifts in this parameter can be used to identify more than Level 1 damage. In other words, the frequencies generally cannot provide spatial information about structural changes. An exception to this limitation occurs at higher modal frequencies, where the modes are associated with local responses. However, the practical limitations involved with the excitation and extraction of these local modes, caused in part by high modal density, can make them difficult to identify. Multiple frequency shifts can provide spatial information about structural damage because changes in the structure at different locations will cause different combinations of changes in the modal frequencies. However, as pointed out by several authors, there are often an insufficient number of frequencies with significant enough changes to determine the location of the damage uniquely.

The Forward Problem

The forward problem, which usually falls into the category of Level 1 damage identification, consists of calculating frequency shifts from a known type of damage. Typically, the damage is modeled mathematically, then the measured frequencies are compared to the predicted frequencies to determine the damage. This method was used extensively by the previously mentioned offshore oil industry investigators.

As an example, Cawley and Adams (1979) give a formulation to detect damage in composite materials from frequency shifts. They start with the ratio between frequency shifts for two different modes. A grid of possible damage points is considered, and an error term is constructed that relates the measured frequency shifts to those predicted by a model based on a local stiffness reduction. A number of mode pairs is considered for each potential damage location, and the pair giving the lowest error indicates the location of the damage. The formulation does not account for possible multiple-damage locations. Special consideration is given to the anisotropic behavior of the composite materials.

Friswell, et al. (1994) present the results of an attempt to identify damage based on a known catalog of likely damage scenarios. The authors presumed that an existing model of the structure is highly accurate. Using this model, they computed frequency shifts of the first several modes for both the undamaged structure and all the postulated damage scenarios. Then ratios of all the frequency shifts were calculated. For the candidate structure, the same ratios were computed, and a power-law relation was fit to these two sets of numbers. When the body of data is noise-free, and when the candidate structure lies in the class of assumed damages, the correct type of damage should produce a fit that is a line with unity slope. For all other types of damage the fit will be inexact. The likelihood of damage was keyed on the quality of the fit to each pattern of known damage. Two measures of fit were used: the first was related to the correlation coefficient; the second was a measure of how close the exponent and coefficient were to unity. Both measures were defined on a scale from 0 to 100. It was hypothesized that damage was present when both measures were near 100.

Juneja, et al. (1997) present a forward technique called contrast maximization to match the response of the damaged structure to a database of structural responses to locate the damage. They also develop a predictive measure of the detectability of the damage. Gudmundson, (1982), Tracy and Pardoen, (1989), and Penny, et al. (1993) present other approaches to the forward problem.

The Inverse Problem

The inverse problem, which is typically Level 2 or Level 3 damage identification, consists of calculating the damage parameters, e.g., crack length and/or location, from the frequency shifts. Lifshitz and Rotem (1969) present what may be the first journal article to propose damage detection via vibration measurements. They look at the change in the dynamic moduli, which can be related to the frequency shift, as indicating damage in particle-filled elastomers. The dynamic moduli, which are the slopes of the extensional and rotational stress-strain curves under dynamic loading, are computed for the test articles from a curve-fit of the measured stress-strain relationships, at various levels of filling.

Stubbs and Osegueda (1990a, 1990b) developed a damage detection method using the sensitivity of modal frequency changes that is based on work by Cawley and Adams (1979). In this method, an error function for the each mode and each structural member is computed assuming that only one member is damaged. The member that minimizes this error is determined to be the damaged member. This method is demonstrated to produce more accurate results than their previous method in the case where the number of members is much greater than the number of measured modes. The authors point out that this frequency-change sensitivity method relies on sensitivity matrices that are computed using a FEM. This requirement increases the computational burden of these methods and also increases the dependence on an accurate prior numerical model. To overcome this drawback, Stubbs, et al. (1992) developed a damage index method, which is presented in the section on methods that use mode shape curvature changes.

Morassi (1997) presents an inverse technique to localize notch effects in steel frames using changes in modal frequency. This study focuses particularly on the accuracy of the assumed reference (undamaged) structural configuration and the practicality of making vibration measurements in the field. Koh, et al. (1995) use a recursive method based on static condensation to locate damage based on measured modal frequencies.

Further examples of inverse methods for examining changes in modal frequencies for indications of damage are presented by: Adams, et al. (1978); Wang and Zhang (1987); Stubbs, et al. (1990); Hearn and Testa (1991); Richardson and Mannan (1992); Sanders, et al. (1992); Narkis (1994); Brincker, et al. (1995); Balis Crema, et al. (1995); Skjaerbaek, et al. (1996a); Al-Qaisia and Meneghetti (1997); and Villemure, et al. (1996).

MODE SHAPE CHANGES

West (1984) presents what is possibly the first systematic use of mode shape information for the location of structural damage without the use of a prior FEM. The author uses the modal assurance criteria (MAC) to determine the level of correlation between modes from the test of an undamaged Space Shuttle Orbiter body flap and the modes from the test of the flap after it has been exposed to acoustic loading. The mode shapes are partitioned using various schemes, and the change in MAC across the different partitioning techniques is used to localize the structural damage.

Fox (1992) shows that single-number measures of mode shape changes such as the MAC are relatively insensitive to damage in a beam with a saw cut. Again this highlights the problem that too much data compression can cause in damage identification. "Node line MAC," a MAC based on measurement points close to a node point for a particular mode, was found to be a more sensitive indicator of changes in the mode shape caused by damage. Graphical comparisons of relative changes in mode shapes proved to be the best way of detecting the damage location when only resonant frequencies and mode shapes were examined. A simple method of correlating node points—in modes that show relatively little change in resonant frequencies—with the corresponding peak amplitude points—in modes that show large changes in resonant frequencies—was shown to locate the damage. The author also presents a method of scaling the relative changes in mode shape to better identify the location of the damage.

Mayes (1992) presents a method for model error localization based on mode shape changes known as structural translational and rotational error checking (STRECH). By taking ratios of relative modal displacements, STRECH assess the accuracy of the structural stiffness between two different structural degrees of freedom (DOF). STRECH can be applied to compare the results of a test with an original FEM or to compare the results of two tests.

Ratcliffe (1997) presents a technique for locating damage in a beam that uses a finite difference approximation of a Laplacian operator on mode shape data. Cobb and Liebst (1997) present a method for prioritizing sensor locations for structural damage identification based on an eigenvector sensitivity analysis. Skjaeraek, et al. (1996b) examine the optimal sensor location issue for detecting structural damage based on changes in mode shapes and modal frequencies using a substructure iteration method.

Yuen (1985); Rizos, et al. (1990); Osegueda, et al. (1992); Kam and Lee (1992); Kim, et al. (1992); Srinivasan and Kot (1992); Ko, et al. (1994); Salawu and Williams (1994, 1995); Lam, et al. (1995); Salawu (1995); Salawu (1997); and Saitoh and Takei (1996) provide examples of other studies that examine changes in mode shapes. The studies focus primarily on MAC and coordinate MAC (COMAC) values to identify damage.

MODE SHAPE CURVATURE/STRAIN MODE SHAPE CHANGES

An alternative to using mode shapes to obtain spatial information about sources of vibration changes is using mode shape derivatives, such as curvature. It is first noted that for beams, plates, and shells there is a direct relationship between curvature and bending strain. Some researchers discuss the practical issues of measuring strain directly or computing it from displacements or accelerations.

Pandey, et al. (1991) demonstrate that absolute changes in mode shape curvature can be a good indicator of damage for the FEM beam structures they consider. The curvature values are computed from the displacement mode shape using the central difference operator.

Stubbs, et al. (1992) present a method based on the decrease in modal strain energy between two structural DOF, as defined by the curvature of the measured mode shapes. Topole and Stubbs (1995a, 1995b) examine the feasibility of using a limited set of modal parameters for structural damage detection. In a more recent publication, Stubbs and Kim (1996) examine the feasibility of localizing damage using this technique without baseline modal parameters.

Chance, et al. (1994) found that numerically calculating curvature from mode shapes resulted in unacceptable errors. They used measured strains instead to measure curvature directly, which dramatically improved results.

Chen and Swamidas (1994); Dong, et al. (1994); Kondo and Hamamoto (1994); Nwosu, et al. (1995); and Yao and Chang (1995) present other studies that identify damage from changes in mode shape curvature or strain-based mode shapes.

METHODS BASED ON DYNAMICALLY MEASURED FLEXIBILITY

Another class of damage identification methods uses the dynamically measured flexibility matrix to estimate changes in the static behavior of the structure. Because the flexibility matrix is defined as the inverse of the static stiffness matrix, the flexibility matrix relates the applied static force and resulting structural displacement. Thus, each column of the flexibility matrix represents the displacement pattern of the structure associated with a unit force applied at the corresponding DOF. The measured flexibility matrix can be estimated from the mass-normalized measured mode shapes and frequencies. The formulation of the flexibility matrix by this method is approximate due to the fact that only the first few modes of the structure (typically the lowest-frequency modes) are measured. The synthesis of the complete static flexibility matrix would require the measurement of all of the mode shapes and frequencies.

Typically, damage is detected using flexibility matrices by comparing the flexibility matrix synthesized using the modes of the damaged structure to the flexibility matrix synthesized using the modes of the undamaged structure or the flexibility matrix from a FEM. Because of the inverse relationship to the square of the modal frequencies, the measured flexibility matrix is most sensitive to changes in the lower-frequency modes of the structure.

Comparison of Flexibility Changes

Aktan, et al. (1994) propose the use of measured flexibility as a “condition index” to indicate the relative integrity of a bridge. They apply this technique to 2 bridges and analyze the accuracy of the flexibility measurements by comparing the measured flexibility to the static deflections induced by a set of truck-load tests.

Pandey and Biswas (1994,1995) present a damage-detection and -location method based on changes in the measured flexibility of the structure. This method is applied to several numerical examples and to an actual spliced beam where the damage is linear in nature. Results of the numerical and experimental examples showed that estimates of the damage condition and the location of the damage could be obtained from just the first two measured modes of the structure.

Toksoy and Aktan (1994) compute the measured flexibility of a bridge and examine the cross-sectional deflection profiles with and without a baseline data set. They observe that anomalies in the deflection profile can indicate damage even without a baseline data set.

Mayes (1995) uses measured flexibility to locate damage from the results of a modal test on a bridge. He also proposes a method for using measured flexibility as the input for a damage-detection method (STRECH) which evaluates changes in the load-deflection behavior of a spring-mass model of the structure.

Peterson, et al. (1995) propose a method for decomposing the measured flexibility matrix into elemental stiffness parameters for an assumed structural connectivity. This decomposition is accomplished by projecting the flexibility matrix onto an assemblage of the element-level static structural eigenvectors.

Zhang and Aktan (1995) suggest that changes in curvatures of the uniform load surface (deformed shape of the structure when subjected to a uniform load), calculated using the uniform load flexibilities, are a sensitive indicator of local damage. The authors state that changes in the uniform load surface are appropriate to identify uniform deterioration. A uniform load flexibility matrix is constructed by summing the columns of the measured flexibility matrix. The curvature is then calculated from the uniform load flexibilities using a central difference operator.

Unity Check Method

The unity check method is based on the pseudoinverse relationship between the dynamically measured flexibility matrix and the structural stiffness matrix. An error matrix is defined which measures the degree to which this pseudoinverse relationship is satisfied. The relationship uses a pseudoinverse rather than an inverse since the dynamically measured flexibility matrix is typically rank-deficient.

Lim (1990) proposes the unity check method for locating modeling errors and uses the location of the entry with maximum magnitude in each column to determine the error location. He applies the method to FEM examples and also investigates the sensitivity of the method to non-orthogonality in the measured modes.

Lim (1991) extends the unity check method to the problem of damage detection. He defines a least-squares problem for the elemental stiffness changes—which are consistent with the unity check error—in potentially damaged members.

Stiffness Error Matrix Method

The stiffness error matrix method is based on the computation of an error matrix that is a function of the flexibility change in the structure and the undamaged stiffness matrix. He and Ewins (1986) present the stiffness error matrix as an indicator of errors between measured parameters and analytical stiffness and mass matrices. For damage identification, the stiffness matrix generally provides more information than the mass matrix, so it is more widely used in the error matrix method.

Gysin (1986) demonstrates the dependency of this method on the type of matrix reduction used and on the number of modes used to form the flexibility matrices. The author compared the reduction techniques of elimination, Guyan-reduction, and indirect reduction, and found that the latter two techniques gave acceptable results, while the first technique did not.

Park, et al. (1988) present a weighted error matrix, where the entries are divided by the variance in natural frequency resulting from damage in each member. The authors apply their formulation to both beam models and plate models.

Effects of Residual Flexibility

The residual flexibility matrix represents the contribution to the flexibility matrix from modes outside the measured bandwidth so that the exact flexibility matrix can be related to the measured modes and the residual flexibility. Doebling, et al. (1996b) and Doebling (1995) present a technique to estimate the unmeasured partition of the residual flexibility matrix because only one column of the frequency response function (FRF) matrix can be measured for each modal excitation DOF. This technique does not add any new information into the residual flexibility, but it does complete the reciprocity of the residual flexibility matrix so that it can be used in the computation of measured flexibility. The authors demonstrate that the inclusion of the measured residual flexibility in the computation of the measured flexibility matrix yields a more accurate estimate of the static flexibility matrix.

Changes in Measured Stiffness Matrix

A variation on the use of the dynamically measured flexibility matrix is the use of the dynamically measured stiffness matrix, defined as the pseudoinverse of the dynamically measured flexibility matrix. Similarly, the dynamically measured mass and damping matrices can be computed. Salawu and Williams (1993) use direct comparison of these measured parameter matrices to estimate the location of damage.

Peterson, et al. (1993) propose a method to use the measured stiffness and mass matrices to locate damage by solving an “inverse connectivity” problem, which evaluates the change in impedance between two structural DOF to estimate the level of damage in the connecting members.

METHODS BASED ON UPDATING STRUCTURAL MODEL PARAMETERS

Another class of damage identification methods is based on the modification of structural model matrices such as mass, stiffness, and damping to reproduce as closely as possible the measured static or dynamic response from the data. These methods solve for the updated matrices (or perturbations to the nominal model that produce the updated matrices) by forming a constrained optimization problem based on the structural equations of motion, the nominal model, and the measured data. Comparisons of the updated matrices to the original correlated matrices provide an indication of damage and can be used to quantify the location and extent of damage. The methods use a common basic set of equations, and the differences in the various algorithms can be classified as follows:

1. Objective function to be minimized
2. Constraints placed on the problem
3. Numerical scheme used to implement the optimization

The following sections describe each of the classification items in this list. For the formulas and equations for each of these sections, please refer to Doebling, et al. (1996a).

Objective Functions and Constraints

There are several different physically based equations that are used as either objective functions or constraints for the matrix update problem, depending upon the update algorithm. The structural equations of motion are the basis for the “modal force error equation.” It is first assumed that the structural eigenequation is satisfied for all measured modes. Substituting the eigenvalues (modal frequencies) and eigenvectors (mode shapes) measured from the damaged structure into this equation along with the mass and stiffness matrix from the undamaged structure yields a vector that is defined as the “modal force error,” or “residual force.” As described by Ojalvo and Pilon (1988), this vector represents the harmonic force excitation that would have to be applied to the undamaged structure at the damaged frequency so that the structure would respond with the damaged mode shape.

There are several methods that have been used to compute the analytical model matrices of the damaged structure such that the resulting equation of motion (EOM) is balanced and the modal force error is minimized. The modal force error is used as both an objective function and a constraint in the various methods described below. Preservation of the property matrix symmetry is used as a constraint. Preservation of the property matrix sparsity (the zero/nonzero pattern of the matrix) is also used as a constraint. The preservation of sparsity is one way to preserve the allowable load paths of the structure in the updated model. Preservation of the property matrix positivity is also used as a constraint.

Optimal Matrix Update Methods

Methods that use a closed-form direct solution to compute the damaged model matrices or the perturbation matrices are commonly referred to as optimal matrix update methods. Smith and Beattie (1991a), Zimmerman and Smith (1992), Hemez (1993), and Kaouk (1993) have published reviews of these methods. The problem is generally formulated as a Lagrange multiplier or penalty-based optimization.

Baruch and Bar Itzhack (1978), Kabe (1985), and Berman and Nagy (1983) have a common formulation of the optimal update problem that is essentially minimization of the Frobenius norm of global parameter matrix perturbations using zero modal force error and property matrix symmetry as constraints.

Chen and Garba (1988a, 1988b) present a method for minimizing the norm of the model property perturbations with a zero modal force error constraint. They also enforce a connectivity constraint to impose a known set of load paths onto the allowable perturbations. The updates are thus obtained at the element parameter level, rather than at the matrix level. This method is demonstrated on a truss FEM.

Another approach to this problem used by Kammer (1988) and Brock (1968) can be formulated as minimization of modal force error with a property matrix symmetry constraint. The symmetry constraint preserves the reciprocity condition in the updated structural model.

McGowan, et al. (1990) report ongoing research that examines stiffness matrix adjustment algorithms for application to damage identification. Based on measured mode shape information from sensor locations that are typically fewer than the DOF in an analytical model, mode shape expansion algorithms are employed to extrapolate the measured mode shapes such that they can be compared with analytical model results. These results are used to update the stiffness matrix while maintaining the connectivity and sparsity of the original matrix.

Smith and Beattie (1991a) extend the formulation of Kabe (1985) to include a sparsity preservation constraint and also formulate the problem as the minimization of both the perturbation matrix norm and the modal force error norm subject to the symmetry and sparsity constraints.

Smith (1992) presents an iterative approach to the optimal update problem that enforces the sparsity of the matrix at each iteration cycle. Multiplying each entry in the stiffness update by either one or zero enforces the sparsity pattern. Kim and Bartkowicz (1993) investigate damage detection capabilities with respect to various matrix update methods, model reduction methods, mode shape expansion methods, numbers of damaged elements, numbers of sensors, numbers of modes, and levels of noise. The authors develop a hybrid model reduction / eigenvector expansion approach to match the order of the undamaged analytical model and the damaged test mode shapes in the matrix update. They also introduce a more realistic noise level into frequencies and mode shapes for numerical simulation. From both numerical and experimental studies, the authors showed that the number of sensors is the most critical parameter for damage detection, followed by the number of measured modes. Lindner, et al. (1993) present an optimal update technique that formulates an overdetermined system for a set of damage parameters representing reductions in the extensional stiffness values for each member. The value represents the amount of stiffness reduction in that member. Lindner and Kirby (1994) extend the technique to account for changes in elemental mass properties.

Liu (1995) presents an optimal update technique for computing the elemental stiffness and mass parameters for a truss structure from measured modal frequencies and mode shapes. The method minimizes the norm of the modal force error. The author demonstrates that if sufficient modal data are available, the elemental properties can be directly computed using the measured modal frequencies, measured mode shapes, and two matrices which represent the elemental orientations in space and the global connectivity of the truss. In this case, the solution for the elemental properties is shown to be unique and globally minimal. The method is used to locate a damaged member in a FEM of a truss using the first four measured modes in sets of three at a time.

Another type of approach to the optimal matrix update problem involves the minimization of the rank of the perturbation matrix, rather than the norm of the perturbation matrix. This approach is motivated by the observation that damage will tend to be concentrated in a few structural members, rather than distributed throughout a large number of structural members. Thus, the perturbation matrices will tend to be of small rank. This approach has been published extensively by Zimmerman and Kaouk (see Refs. below). The solution for the perturbation matrices is based on the theory that the a unique minimum rank matrix solution of the underdetermined system exists.

Zimmerman and Kaouk (1994) present the basic minimum rank perturbation theory (MRPT) algorithm. A nonzero entry in the damage vector is interpreted as an indication of the location of damage. The resulting perturbation has the same rank as the number of modes used to compute the modal force error. It is demonstrated that the MRPT algorithm preserves the rigid body modes of the structure and the effects of measurement and expansion errors in the mode shapes are demonstrated and discussed.

Kaouk and Zimmerman (1994a) further develop this algorithm and demonstrate how perturbations to two of the property matrices can be estimated simultaneously by using complex conjugates of the modal force error equation. The method is demonstrated numerically for a truss with assumed proportional damping. Also, the technique is used experimentally to locate a lumped mass attached to a cantilevered beam.

Kaouk and Zimmerman (1994b) extend the MRPT algorithm to estimate mass, stiffness, and proportional damping perturbation matrices simultaneously. The computation of these individual perturbation matrices is accomplished by exploiting the cross-orthogonality conditions of the measured mode shapes with respect to the damaged property matrices. The authors examine the results by computing a cumulative damage vector.

Kaouk and Zimmerman (1994c) present a technique that can be used to implement the MRPT algorithm with no original FEM. The technique involves using a baseline data set to correlate an assumed mass and stiffness matrix, so that the resulting updates can be used as the undamaged property matrices.

Zimmerman and Simmermacher (1994, 1995) compute the stiffness perturbation resulting from multiple static load and vibration tests. This technique is proposed partially as a method for circumventing the mismatch in the number of modes between test and FEM. They apply this technique to a FEM of a structure similar to a NASA test article. They also present two techniques for overcoming the rank deficiency that exists in the residual vectors when the results of one static or modal test are linear combinations of the results of previous tests.

Kaouk and Zimmerman (1995a) introduce a partitioning scheme into the MRPT algorithm by writing the parameter matrix perturbations as sums of elemental or substructural perturbations. The partitioning procedure reduces the rank of the unknown perturbation matrices and thus reduces the number of modes required to successfully locate the damage. The technique is demonstrated on data from the NASA 8-bay Dynamic Scale-Model Truss (DSMT) testbed. In a related paper, Kaouk and Zimmerman (1995b) further examine the reduction of the number of modes required for model updating using a two-level matrix partitioning technique.

Zimmerman, et al. (1995a) extend the theory to determine matrix perturbations directly from measured FRFs. This method is implemented by solving for the perturbation in the dynamic impedance matrix from the generalized off-resonance, dynamic-force residual equation. They discuss the benefits of this formulation, including the elimination of the need to match modes between FEM and test, reduction in the amount of frequencies required in the test (and thus test time), and the elimination of the need to perform modal parameter identification.

Zimmerman, et al. (1995b) investigate the role of engineering insight and judgment in the implementation of the MRPT techniques to damage detection. Specifically, the issues of evaluation of the damage location, selection of how many measured modes to use, filtering of the eigenvectors and the damage vector, and decomposition of the damage vector into contributions from individual property matrices are addressed. This paper also contains a list of publications related to the theory and application of MRPT.

Doebling (1996) presents a method to compute a minimum-rank update for the elemental parameter vector, rather than for global or elemental stiffness matrices. The method uses the same basic formulation as the MRPT, but constrains the global stiffness matrix perturbation to be an explicit function of the diagonal elemental stiffness parameter perturbation matrix that preserves the finite element strain-displacement relations. A limitation of this method as with all minimum-rank procedures is that the rank of the perturbation is always equal to the number of modes used in the computation of the modal force error.

Sensitivity-Based Update Methods

Another class of matrix update methods is based on the solution of a first-order Taylor series that minimizes an error function of the matrix perturbations. Such techniques are known as sensitivity-based update methods. An exhaustive list and classification of various sensitivity-based update techniques is given in Hemez (1993). The basic theory is the determination of a modified model parameter vector (consisting of material and/or geometric parameters), where the parameter perturbation vector is computed from the Newton-Raphson iteration problem for minimizing an error function.

A main difference between the various sensitivity-based update schemes is the method used to estimate the sensitivity matrix. Basically, either the experimental or the analytical quantities can be used in the differentiation. For experimental sensitivity, the orthogonality relations can be used to compute the modal parameter derivatives. Norris and Meirovitch (1989), Haug and Choi (1984) and Chen and Garba (1980) have proposed such an approach.

Analytical sensitivity methods usually require the evaluation of the stiffness and mass matrix derivatives, which are less sensitive than experimental sensitivity matrices to noise in the data and to large perturbations of the parameters.

Ricles (1991) presents a methodology for sensitivity-based matrix update, which takes into account variations in system mass and stiffness, center of mass locations, changes in natural frequency and mode shapes, and statistical confidence factors for the structural parameters and experimental instrumentation. The method uses a hybrid analytical/experimental sensitivity matrix, where the modal parameter sensitivities are computed from the experimental data, and the matrix sensitivities are computed from the analytical model. This method is further developed and applied to more numerical examples by Ricles and Kosmatka (1992).

Sanayei and Onipede (1991) present a technique for updating the stiffness parameters of a FEM using the results of a static load-displacement test. A sensitivity-based, element-level parameter update scheme is used to minimize the error between the applied forces and forces produced by applying the measured displacements to the model stiffness matrix. The sensitivity matrix is computed analytically. The structural DOF are partitioned such that the locations of the applied loads and the locations of the measured displacements are completely independent. The technique is demonstrated on two FEM examples.

In a related paper, Sanayei, et al. (1992) examine the sensitivity of the previous algorithm to noisy measurements. The influence of the selected measurement DOF set on the errors in the identified parameters is studied. A heuristic method is proposed that recursively eliminates the measurement DOF that the elemental stiffness parameters are the most sensitive to. In this manner, the full FEM DOF set is reduced to a manageable size while preserving the ability to identify the structural stiffness parameters. In later work, Sanayei and Saletnik (1995a, 1995b) extend the algorithm and the error analysis to use static strain, rather than displacement, measurements.

Hemez and Farhat (1995) present a sensitivity-based matrix update procedure that formulates the sensitivities at the element level. This has the advantage of being computationally more efficient than forming the sensitivities at the global matrix level. It also allows the analysis to “focus” on damage in specific members. A modified version of this algorithm, developed by Alvin (1996), improves the convergence, utilizes a more realistic error indicator, and allows the incorporation of statistical confidence measures for both the initial model parameters and the measured data.

Eigenstructure Assignment Method

Another matrix update method, known as “eigenstructure assignment,” is based on the design of a fictitious controller that would minimize the modal force error. The controller gains are then interpreted as parameter matrix perturbations to the undamaged structural model. Lim (1994, 1995) provides a clear overview of the eigenstructure assignment technique: Consider the basic structural EOM with a controller. Suppose that the control gains are selected such that the modal force error between the nominal structural model and the measured modal parameters from the damaged structure is zero. Then the “best achievable eigenvectors” can be written in terms of the measured eigenvectors. The relationship between the best achievable eigenvectors and the measured eigenvectors is then used as a measure of damage location. Specifically, if damage is in a particular member, then the measured and best achievable eigenvectors are identical. Thus, the angle between the two vectors gives an indicator of how much a particular member contributes to the change in a particular mode. This information can be used to hypothesize the location of the structural damage. The magnitude of the damage is then computed using the eigenstructure assignment technique such that the best achievable eigenvectors, undamaged model matrices, and controller satisfy the modal force error equation. Lim and Kashangaki (1994) introduce the use of the best achievable eigenvectors for the location of structural damage and apply the technique to the detection of damage in an 8-bay cantilevered truss.

Zimmerman and Kaouk (1992) implement such an eigenstructure assignment technique for damage detection. They include algorithms to improve the assignability of the mode shapes and preserve sparsity in the updated model. They apply their technique to the identification of the elastic modulus of a cantilevered beam.

Lindner and Goff (1993) define damage coefficients for each structural member. They then use an eigenstructure assignment technique to solve for the damage coefficient for each member. They apply this technique to detect simulated damage in a 10-bay truss FEM.

Lim (1994, 1995) applies a constrained eigenstructure technique experimentally to a twenty-bay planar truss. His approach identifies element-level damage directly, rather than finding perturbations to the stiffness matrix. The computation of element-level perturbations is accomplished by diagonalizing the control gains, then interpreting the diagonal entries as changes to the elemental stiffness properties. The technique is shown to work well even with limited instrumentation.

Schulz, et al. (1996) present a technique similar to eigenstructure assignment known as “FRF assignment.” The authors formulate the problem as a linear solution for element-level stiffness and mass perturbation factors. They point out that using FRF measurements directly to solve the problem is more straightforward than extracting mode shapes. They use measured mobility functions (FRFs from velocity measurements) to obtain higher numerical accuracy, since the velocity response is flatter over the entire spectrum than either the displacement or acceleration response. The technique is applied to an FEM of a bridge structure. Cobb and Liebst (1997) present another eigenstructure assignment-based method for structural damage identification.

Hybrid Matrix Update Methods and Other Considerations

Baruh and Ratan (1993) use the residual modal force as an indicator of damage location. They separate the residual modal force into the effects of identification error in the measurements, modeling error in the original structural model, and modal force error resulting from structural damage. They examine the sensitivity of the damage location solution to errors in the original structural model and to inaccuracies in the modal identification procedure.

Kim and Bartkowicz (1993, 1994) and Kim, et al. (1995a) present a two-step damage-detection procedure for large structures with limited instrumentation. The first step uses optimal matrix update to identify the region of the structure where damage has occurred. The second step is a sensitivity-based method, which locates the specific structural element where damage has occurred. The first advantage of this approach lies in the computational efficiency of the optimal update method in locating which structural parameters are potentially erroneous. The second advantage lies in the small number of parameters updated by the sensitivity-based technique.

Li and Smith (1994, 1995) present a hybrid model update technique for damage identification that uses a combination of the sensitivity and optimal-update approaches. This method constrains the stiffness matrix perturbation to preserve the connectivity of the FEM, and the solution minimizes the magnitude of the vector of perturbations to the elemental stiffness parameters. The hybrid technique is shown to be more computationally efficient than the iterative sparsity-preserving algorithm presented by Smith (1992).

Dos Santos and Zimmerman (1996a) examine the effects of model reduction via component mode synthesis (specifically using the Craig-Bampton technique) on the accuracy of damage identification results obtained using the MRPT force residual and angle residual vectors. Numerical examples were conducted using a FEM of a clamped-clamped beam divided into five substructures of 3 or 4 elements each. Damage was simulated on one of the elements within one of the substructures by reducing the cross-sectional moment of inertia by 25%. The results indicated that the MRPT force residual vector was unable to accurately locate the damaged substructure. The results of applying the angle residual vector indicated that the damaged substructure could be identified using a highly truncated component mode set, and the damaged element could be identified using a more rich component mode set.

Dos Santos and Zimmerman (1996b) propose a method for damage identification that uses MRPT in conjunction with ordinary least-squares estimation to preserve the connectivity of the FEM during the update procedure. The method produces estimates of the damage extent in the form of element-level stiffness parameter perturbations. The procedure is conducted in two steps: First, the damaged global stiffness matrix perturbation is estimated using the MRPT algorithm. Next, a set of parameters representing the loss of stiffness in each element is estimated by minimizing the error between the MRPT matrix perturbation and the global stiffness matrix perturbation computed using the elemental stiffness matrices and the stiffness reduction parameters. The unique estimation of the parameters requires that the number of measurement be greater than or equal to the number of parameters being estimated.

Gafka and Zimmerman (1996) evaluate the performance of a mode shape expansion algorithm known as Least-Squares Dynamic Residual Force Minimization with Quadratic Measurement Error Inequality Constraint (LSQIC). The method is used to estimate the component of the measured mode shapes at the unmeasured FEM DOF. The method minimizes the error in the residual modal force vector that results from substituting the expanded measured mode shape into the FEM eigenequation. The magnitude of the difference between the expanded and measured mode shape at the measurement DOF is constrained to be less than a certain fraction of the magnitude of the measured mode shape. The method is compared to two standard techniques — Guyan (or static) expansion and dynamic expansion — for application to both FEM model correlation and damage identification. The results demonstrate that the expansion method allows for accurate FEM correlation in the general case where the errors are distributed somewhat evenly in the structure. However, in the case of damage identification, where the discrepancies between the test data and the model are isolated at a few DOF, a smearing effect resulting from the use of a singular value decomposition in the solution procedure can impede accurate identification of the damage.

Yao and Natke (1994) present a model-based approach for damage detection and structural reliability evaluation based on parameter changes of the verified mathematical model. Hjelmstad and Shin (1997) present another damage detection technique based on FEM updating. This procedure uses an adaptive parameter-grouping scheme to localize the damage under the realistic conditions of spatially sparse measurement data. A technique is proposed to determine a threshold above which damage can be discriminated from background noise.

Doebling, et al. (1997) examine the effects of mode selection on the accuracy of the damage location and extent identified using a FEM refinement scheme. A method is proposed to select modes for the update based on modal strain energy content. James and Zimmerman (1997) present a study of the model order reduction and measured data expansion processes. The magnitude of errors introduced by the processes and the preservation of the original load paths are some of the topics addressed in this paper.

CRITICAL ISSUES FOR FUTURE RESEARCH IN DAMAGE IDENTIFICATION AND HEALTH MONITORING

This section contains a summary of the critical issues, as perceived by the authors, in the field of vibration-based structural damage identification and health monitoring. The purpose behind this section is to focus on the issues that must be addressed by future research to make the identification of damage using vibration measurements a viable, practical, and commonly implemented technology.

One issue of primary importance is the dependence on prior analytical models and/or prior test data for the detection and location of damage. Many algorithms presume access to a detailed FEM of the structure, while others presume that a data set from the undamaged structure is available. Often, the lack of availability of this type of data can make a method impractical for certain applications. While it is doubtful that all dependence on prior models and data can be eliminated, certainly steps can and should be taken to minimize the dependence on such information.

Almost all of the damage-identification methods reviewed in this report rely on linear structural models. Further development of methods that have the ability to account for the effects of nonlinear structural response has the potential to enhance this technology significantly. An example of such a response would be the opening and closing of a fatigue crack during cyclic loading, in either an operational situation or in the case of a forced-vibration test. Many methods are inherently limited to linear model forms and, therefore, cannot account for the nonlinear effects of such a damage scenario. Another advantage of methods that detect nonlinear structural response is that they can often be implemented without detailed prior models. It is of interest to note that the one application where this technology is accepted and commonly used in practice, the monitoring of rotating machinery, relies almost exclusively on the detection of nonlinear response.

The number and location of measurement sensors is another important issue. Many techniques that appear to work well in example cases actually perform poorly when subjected to the measurement constraints imposed by actual testing. Techniques that are to be seriously considered for implementation in the field should demonstrate that they can perform well under the limitations of a small number of measurement locations, and under the constraint that these locations be selected *a priori* without knowledge of the damage location.

An issue that is a point of controversy among many researchers is the general level of sensitivity that modal parameters have to small flaws in a structure. Much of the evidence on both sides of this disagreement is anecdotal because it is only demonstrated for specific structures or systems and not proven in a fundamental sense. This issue is important for the development of health-monitoring techniques because the user of such methods needs to have confidence that the damage will be recognized while the structure still has sufficient integrity to allow repair.

An issue that has received almost no attention in the technical literature is the ability to discriminate between changes in the modal properties resulting from damage and those changes resulting from variations in the measurements. These variations result from changing environmental and/or test conditions and from the repeatability of the tests. A high level of variation in the measurements will prevent the accurate detection of small levels of damage. Mazurek (1997) presents a technique to address the variability issue in the context of vibration-based damage identification. Very few vibration-based damage detection studies report statistical variations associated with the measured modal parameters used in the damage identification process. Even fewer studies report the results of false-positive studies (cases where techniques indicate damage even though the data is from an undamaged structure). Two recent studies (Doebling, et al., 1997a, and Farrar and Jauregui, 1996) have started to examine these issues.

With regard to long-term health monitoring of large structures such as bridges and offshore platforms, the need to reduce the dependence upon measurable excitation forces is noted by many researchers. The ability to use vibrations induced by ambient environmental or operating loads for the assessment of structural integrity is an area that merits further investigation.

The literature also has scarce instances of studies where different health-monitoring procedures are compared directly by application to a common data set. Some data sets, such as the NASA 8-Bay truss data set and the I-40 Bridge data set, have been analyzed by many different authors using different methods. However, the relative merits of these methods and their success in locating the damage have not been directly compared in a sufficiently objective manner. The study of the I-40 Bridge presented in (Farrar and Jauregui, 1996) compares five vibration-based damage identification methods applied to the same data sets.

A final note on future research in the field of vibration-based damage identification: There is a significant need in this field for research on the integration of theoretical algorithms with application-specific knowledge bases and practical experimental constraints. For example, most vibration-based damage identification theories are applied similarly to both an airframe and a highway bridge. However, real-life vibration monitoring of airframes and highway bridges are radically different in terms of both equipment and techniques. Likewise, design margins and periodic maintenance requirements are different for an airframe and a highway bridge. Most (if not all) damage identification techniques proposed in the literature do not take into account these differences.

Overall, it is the opinion of the authors that sufficient evidence exists to promote the use of measured vibration data for the detection of damage in structures, using both forced-response testing and long-term monitoring of ambient signals. It is clear, though, that the literature in general needs to be more focused on the specific applications and industries that would benefit from this technology, such as health monitoring of bridges, offshore oil platforms, airframes, and other structures with long design life, life-safety implications and high capital expenditures. Additionally, research should be focused more on testing of real structures in their operating environment, rather than laboratory tests of representative structures. Because of the magnitude of such projects, more cooperation will be required between academia, industry, and government organizations. If specific techniques can be developed to quantify and extend the life of structures, the investment made in this technology will clearly be worthwhile.

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