Continuous Monitoring of Modal Parameters to Quantify Structural Damage

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Abstract

In this paper, a continuous monitoring system which measures the vibration of a structure, identifies changes in its modal parameters, and predicts occurrences of structural faults is presented. An overall acquisition and computational procedure is presented for detecting and quantifying damage in structures using experimentally derived modal parameters.

The discussion includes measurement techniques, how changes in the modal parameters are caused by physical changes, and the use of a trained neural network for fault location and quantification. Such a system provides a level of accuracy well beyond the peak-picking implementations of traditional predictive maintenance monitoring systems, and is able to benefit from a priori knowledge of the structure's modal properties.

Nomenclature

t = time variable (seconds).

n = number of measured DOFs.

$[M]$ = $(n \text{ by } n)$ mass matrix (force/unit of acceleration).

$\{x''(t)\}$= acceleration response n-vector.

$[C]$ = $(n \text{ by } n)$ damping matrix (force/unit of velocity).

$\{x'(t)\}$ = velocity response n-vector.

$[K]$ = $(n \text{ by } n)$ stiffness matrix (force/unit of displacement).

$\{x(t)\}$ = displacement response n-vector.

$\{f(t)\}$ = excitation force n-vector.

Introduction

Modal testing has become commonplace in many industries, both as an R&D tool, and for trouble shooting noise and vibration problems in operating machinery and equipment. Very little use has been made of this technology, however, for detecting structural faults or defects in structures and operating machinery.

The underlying principle behind the method of fault detection discussed in the paper is that *changes in modes are sensitive indicators of changes in the physical integrity of any mechanical structure.* When a structural fault such as cracking, delamination, unbonding or loosening of a part occurs, this will cause a decrease in stiffness, (and perhaps an increase in damping), in a local region of the structure. This change in the local stiffness and damping properties directly affects the manner in which the structure vibrates when excited by either ambient or artificially applied forces. A very common example of this is a bell. If a bell is cracked, then when it is struck, it will give off a more heavily damped “thud” sound rather than the expected lightly damped ringing sound.

When vibrational changes take place in a structure, these changes can be quantified in commonly understood frequency domain measurements, that are curve fit to extract the modal properties of the damaged structure. These modal properties are then compared with baseline (undamaged) properties, and the changes are input to a neural network, which determines the location and severity of the damage. The overall measurement and computational procedure using in this monitoring system is depicted in Figure 1.

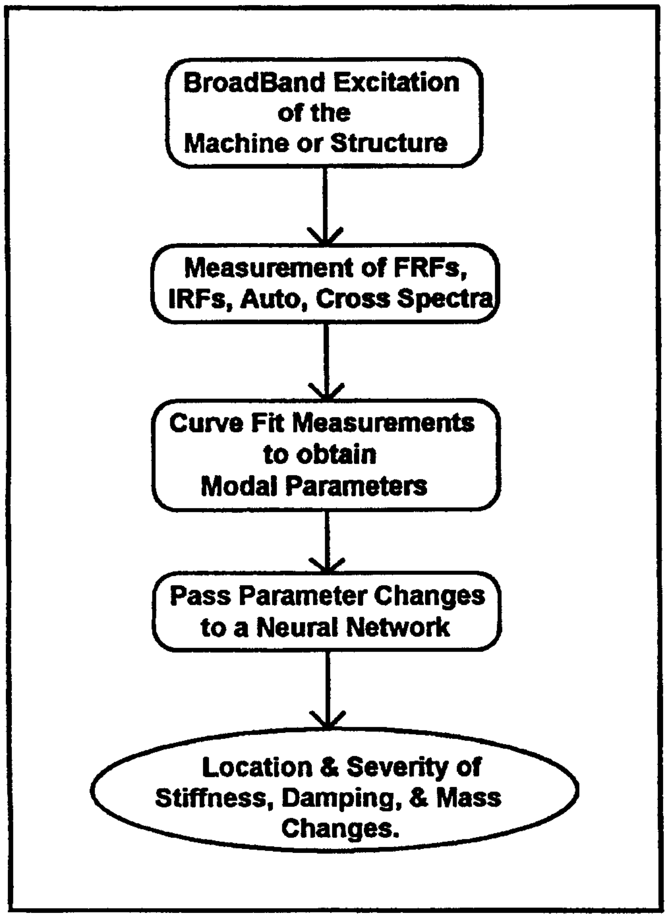

Figure 1. Computational Model for Fault Detection, Location, & Quantification

Advantages of Monitoring Modes on a Continuous Basis

A wide variety of different Non-Destructive Testing (NDT) Methods (listed in Table 1) have been applied to structures in an effort to locate structural faults. However, vibration measurement, and the estimation of modal parameter changes has some inherent advantages for continuous monitoring applications that are not available with other methods.

1. Modal Parameters Can Be Measured On Any Structure That Vibrates.

Modal parameters can be measured from any structure that vibrates, or resonates. A structure will vibrate when energy becomes trapped within its boundaries, and cannot readily escape. Structures that vibrate include most complex structures made of ferrous and non-ferrous metals, and other solid materials such as plastics, graphite epoxies, etc.

2. Modes are *Sensitive Indicators of Physical Changes.*

It is well known among experimentalists, who are familiar with modal testing that modes are very sensitive indicators of changes in the physical (mass, stiffness, or damping) characteristics, or physical constraints (boundary conditions) of a test structure. Anyone who has performed a modal test has probably experienced the strong sensitivity of modal parameters to physical changes in a test setup. Mass loading, ambient temperature changes, and vibration induced changes in the constraints or material properties of the structure will cause changes in its measured modal parameters, thus giving different test results.

Visual Inspection
Magnetic Field
Eddy Current
X-Ray
Ultra Sound
Acoustic Emission
Thermal Contours
Laser Interferometry
Strain Gauge

Table 1. Traditional NDT Methods

3. Changes in Modes Can *Localize* a *Fault.*

The mode shapes of the higher frequency modes of a structure are typically defined (are non-zero) over local regions on the structure. (For this reason, they are called local modes.) Therefore, detected changes in the measured parameters of local modes indicate a fault in a local region of a structure.

4. Faults Can Be Detected in Unmeasured Regions of the Structure.

Most NDT methods require that a measurement be made directly at the fault location in order to detect it. However, modal frequency and damping are *global properties* that can be measured anywhere on the surface of the structure where the mode shape is defined. Due to the *global property* of modal frequency and damping, measurements do not have to be made directly at a fault location in order to detect a change in frequency or damping caused by the fault.

5. *Only* a *Small Number of Measurements are Required*

Only a small number of measurements (ideally only one) are required to monitor modal frequency and damping changes. Modal properties can be estimated from FRFs (frequency response functions), IRFs (impulse response functions), auto power spectrum, and cross power spectrum measurements. The frequencies and damping of *all of the modes* in the measurement frequency range can be estimated from a single measurement.

IRFs and auto power spectrum measurements only require one measurement channel, (i.e. one motion transducer and one data acquisition channel.) IRF measurements also require that an impulsive force be applied to the structure, of course. FRFs and cross power spectra are 2-channel measurements, involving two measurement transducers and two simultaneously acquired signals. A cross power spectrum is formed between two response channels, while an FRF typically requires a response signal and an excitation (force) signal.

6. A Wide Variety of Excitation and Signal Processing Methods Can Be Used.

Advances in FFT (Fast Fourier Transform)-based test equipment and frequency domain parameter estimation (curve fitting) methods have significantly improved the accuracy, and repeatability, with which modal parameters can be identified from test data. Modern modal testing methods include the use of;

- Multiple exciters and a wide variety of excitation signals, including many variations of transient, sine, and random signals. (Artificial excitation is optional, however, and may not be required it the structure is self-excited, or excited by ambient forces.)

- Multi channel data acquisition and MIMO (multi-input multi-output) digital signal processing using the FFT. Ensemble averaging of auto and cross spectra is a straightforward, effective way of removing extraneous noise from measurement signals.

- Multiple reference (Poly Reference) curve fitting of the measurement data to estimate the modal parameters more accurately. Also, using multiple reference measurements for curve fitting further ensures that no modal parameter changes will be missed.

7. Modal Testing is Non-Destructive.

Modal parameters can be estimated from operating data, or from measurements that are made using very low levels of excitation, thus incurring little risk of inadvertently damaging the structure during testing. *Sine wave excitation at the structure's resonant frequencies, which can potentially damage the structure, is not required.* There are other FFT-based signal processing benefits to be gained from using certain broad band random excitation signals as well.

Controlled Excitation Versus Operating Data

Modal properties are independent of structural excitation, and are therefore most commonly obtained from FRF or IRF measurements, which for linear systems don't depend on the excitation.

In a majority of situations, though, the structure may be an operating machine that is self-excited, or is excited by other ambient forces. In both of these cases, the excitation forces cannot be directly measured. When operating data is acquired, auto or cross power spectrum measurements can be used to estimate modal parameters, with one strong assumption:

> *Assumption:* If auto and cross power spectrum measurements are used to estimate modal parameters, then it must be assumed that the auto power spectra of the excitation forces acting on the structure are “relatively flat”, or have identified peaks that are not curve fit as modal peaks.
>
> By “relatively flat” it is meant that the energy input to the structure by the excitation forces is approximately the same over the frequency band where modal parameters will be estimated.

Theoretical Background

The mass, stiffness, and damping properties of a structure determine how it vibrates. Vibration is caused by an exchange of energy between the mass (or inertial) properties and the stiffness (or restoring) properties of a structure. Damping in a structure dissipates vibrational energy, usually as friction heat.

The equations that describe the vibration of a structure are commonly derived by applying Newton's second law to all of the degrees of freedom (DOFs) of interest on the structure. For an experimental situation, this results in a finite set of equations, one for each measured DOF:

$$[M]\{x''(t)\}+[C]\{x'(t)\}+[K]\{x(t)\}=\{f(t)\} \qquad (1)$$

In this model, the excitation forces and responses are functions of time (*t*), and the coefficient matrices $[M]$, $[C]$, and $[K]$ are constants. This dynamic model describes the vibration response of a linear, time invariant structure, subject to any number and kind of externally applied forces, represented by the force vector $\{f(t)\}$. Notice that all solutions to equation (1) are directly influenced by the mass, stiffness, and damping properties of the structure. If the structure is excited with an impulse, such as in the case of striking a bell, equation (1) will yield the impulse response of the structure as a solution. The impulse response of a bell is, of course, its damped ringing sound. The boundary conditions (mountings) of a structure also influence its vibrational response. This certainly agrees with our intuition and experience. A cantilever beam will vibrate differently than a beam that is not fixed at one end.

Equivalent of Structural Dynamics

In addition to its differential equations of motion given in equation (1), the linear dynamics of a structure can also be represented in several other equivalent forms, as shown in Figure 2. Frequency Response Functions (FRFs), Impulse Response Functions (IRFs), and the structure's modal parameters each fully represent the dynamics of the structure. Consequently, Figure 2 indicates that if any of the mass, stiffness, or damping properties of the structure should change, we can expect that its FRFs, IRFs, and modal parameters will change also. Conversely, if the measured FRFs, IRFs, or experimental modal parameters of a structure were to change, we can expect that some of the mass, stiffness, or damping properties will have changed also.

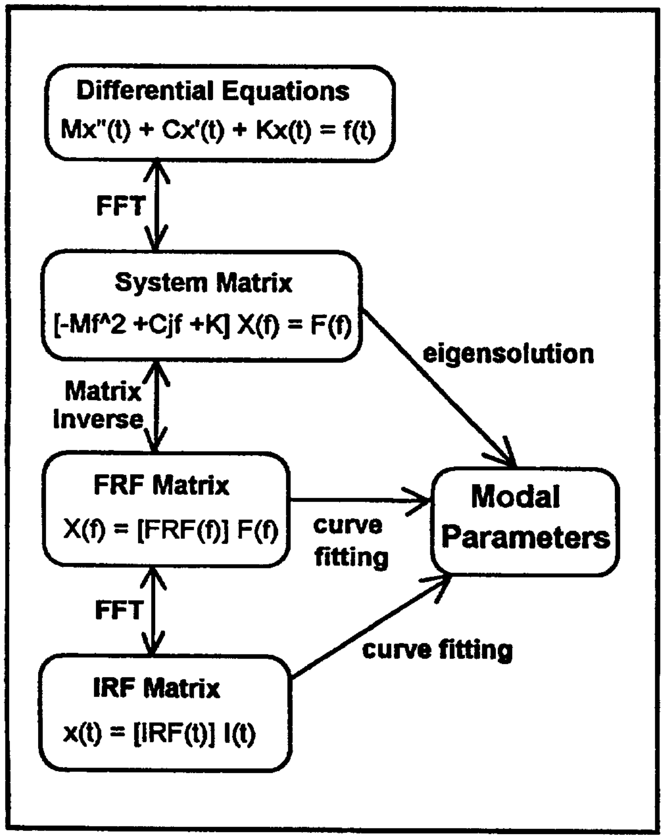

Figure 2. Equivalent Representations of Structural Dynamics

In summary, the modal properties of a structure are directly related to its mass, stiffness, and damping properties. Therefore, changes in the structure's mass, stiffness, or damping properties will cause changes in its modal properties (modal frequencies, modal damping and mode shapes). Changes in the structure's boundary conditions (mountings) will also change its modal parameters. This relationship between changes in physical properties and changes in modal properties can be stated in two ways.

The Forward Problem*:* Changes in the mass, stiffness, and damping properties of a structure will cause *unique changes* in the modal properties of a structure.

The forward problem is solved by finding the eigensolution of a set of mass, stiffness, and damping matrices. The eigensolution process always yields a unique set of modal parameters (eigenvalues and eigenvectors).

The Inverse Problem*:* Changes in the modal properties of a structure will cause *unique changes* in its mass, stiffness, and damping properties.

The solution to the Inverse Problem is derived in Reference [7]. The equations in reference [7] show that changes in a *sufficiently large number* of modes, with mode shapes that are linearly independent of one another, will yield a unique set of mass, stiffness, and damping changes. The Inverse Problem must be solved in order to locate and quantify physical damage on a structure from measured changes in its modal properties.

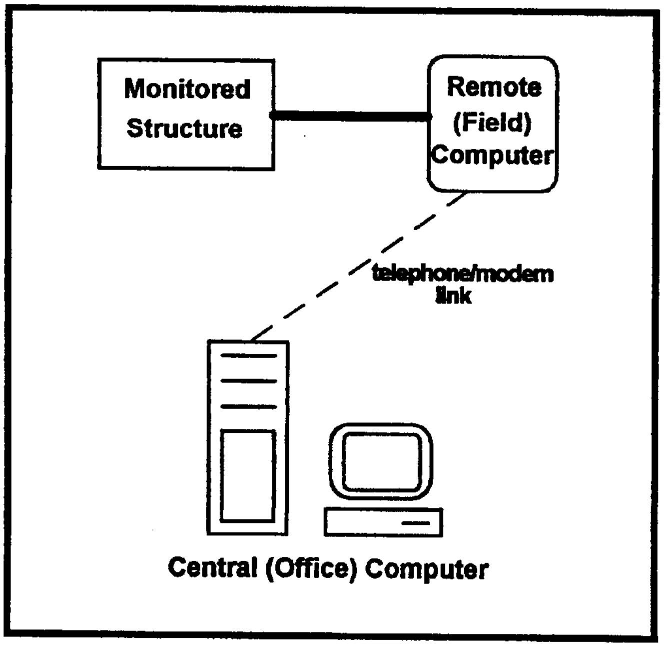

Figure 3. Continuous Monitoring System

Continuous Monitoring System

The continuous monitoring system in which this fault detection method has been implemented is shown in Figure 3. Current PC computer technology makes it economically feasible to install a computer-based multi-channel monitoring system on or near every structure to be monitored. Its modal parameters are then monitored continuously, 24 hours a day. Other operating parameters such as temperatures, pressures, flow rates, electrical currents, etc. are also monitored for predictive maintenance purposes.

The acquired data is saved in the data base of the field computer, on its hard disk drive. Then, on a periodic basis, each field computer data base is transferred to a central computer, via telephone/modem link. Data files containing megabytes of data can be transferred over the phone in minutes, using current day modem technology and data compression methods. Further processing, including neural network processing, is done in the central computer, and data is stored in its archival, (and relational), data base.

Each field monitoring computer can also be programmed to check measured parameters, or combinations of measured parameters, against prescribed alarm conditions. Whenever an alarm condition is encountered, the field computer will immediately notify the central computer, via the telephone/modem link.

The advantages of this system are:

- Critical machinery or structures can be monitored continuously, anywhere in the world that's accessible by a telephone line.
- A cellular phone link can be used to provide access to a local phone network, where necessary.
- Data from a large number of remote monitoring units can be processed with one central computer located anywhere in the world.

Neural Networks

In this application, a neural network has been used to solve a particularly intractable computational problem, namely, locating and quantifying mass, stiffness and damping changes on a structure due to measured changes in its modal parameters.

Attempting to solve the previously defined *Inverse Problem* with a relatively small (practical) number of modal parameter changes yields a rank deficient set of equations. Solving them directly is computationally difficult, if not impossible. (See references [3] and [4].)

Neural networks have been applied recently to a variety of problems that were difficult or impossible to solve by any other method. The strength of neural network solutions lies in their pattern recognition capabilities. When statistical curve fitting, or other equation solving methods fail because of rank deficiency or other related numerical problems, neural networks often give very usable results.

Neural networks were developed to mimic the pattern recognition capabilities of the human brain. Recently, they have been successfully implemented in Optical Character Recognition (OCR) software with a success rate in the high 90 percents, far exceeding previously tried statistical methods.

A prerequisite to the use of a neural network is that it be “trained” before it is used. To be effective, the neural network must be trained over a *sufficiently wide solution space* so that it will give reasonable solutions, even when its input data is noisy and minimal. In this sense, a neural network *interpolates* between solutions that it has been trained on, and yields a solution the “fits” between the known solutions.

In this application, training the network involves feeding it many sets of modal parameter changes together with the mass, stiffness, and damping changes that caused them. (Solutions to the ***Forward Problem**.)* During training, the neural network computes a set of internal weights that best correlate its inputs (modal parameter changes) with its outputs (mass, stiffness, and damping changes).

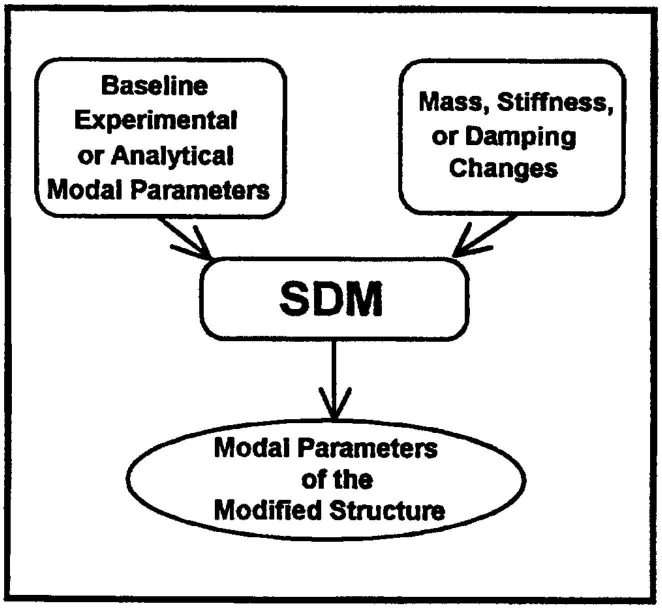

Figure 4. The SDM Method

Using SDM to Train a Neural Network

The SDM (Structural Dynamics Modification) method is an ideal tool for training a neural network for this application. The SDM method is depicted in Figure 4. Given a set of modal parameters from the baseline (undamaged) structure, the SDM algorithm (See Reference [6]) computes the modal parameters of the modified structure due to modifications in its mass, stiffness, or damping matrices. SDM solves the **Forward Problem** very efficiently. As opposed to the time consuming eigensolution process of a finite element program, SDM computes new solutions very rapidly, even on a desktop PC. Furthermore, SDM only requires the modal parameters of the baseline structure, and not its full mass, stiffness, and damping matrices.

SDM can use analytical or experimental modal data as input data for the training process. The use of SDM as a neural network trainer is shown in Figure 5. SDM is used to generate a large set of potential solution pairs (mass, stiffness, and damping changes paired with modal parameter changes) required to train the neural network.

Random mass, stiffness, and damping changes are entered into SDM to generate the required modal parameter changes. 100,000 changes are typically used to train a network. The more training a network receives, the better it will potentially predict the mass, stiffness, and damping changes that caused a given a set of measured modal parameter changes. Once a network has been trained for a particular structure, it can process modal data that was acquired from that structure with the on-line monitoring system.

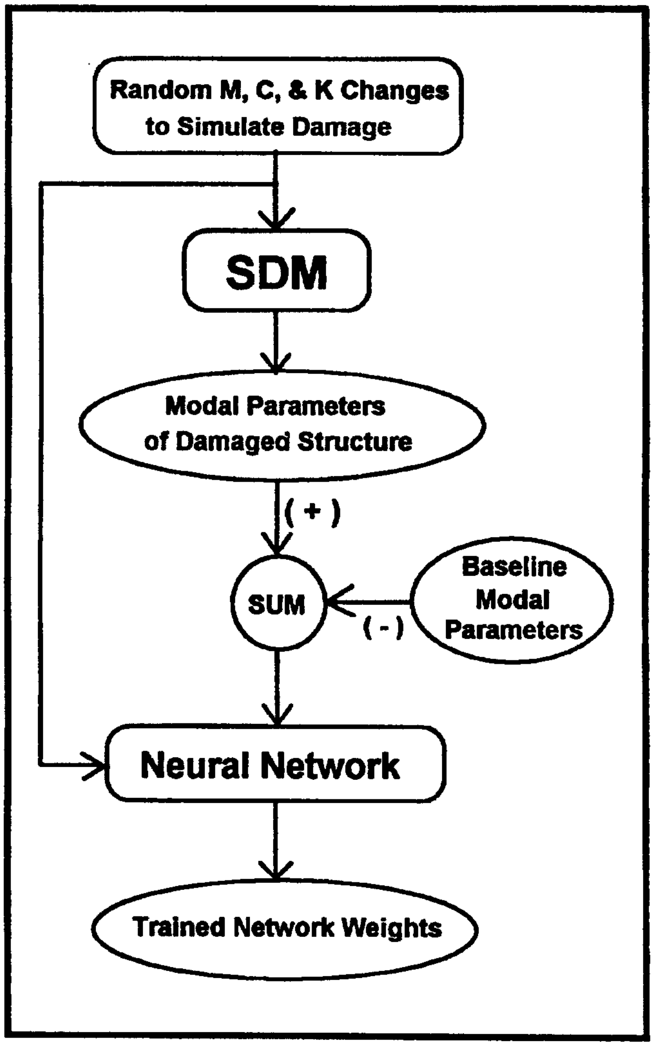

Figure 5. Training the Neural Network

Use of Analytical Modal Data

Typically, analytical mode shapes with very refined spatial resolution (lots of DOFs), compared to experimental mode shapes, can be generated from a finite element model of a structure. When such a finite model is available, the modal parameters from this model can be used as the baseline model for training the neural network. The advantage of the analytical modes is that much finer spatial resolution can be achieved with the neural network solutions, and faults involving many unmeasured DOFs can be trained into the network.

Conclusions

In this paper, we have presented the primary features on a remote continuous monitoring system that uses measured modal data to locate and quantify faults in structures. This design involves a number of new technologies, and an algorithmic approach that we believe uniquely solves a class of predictive maintenance problems. This, in combination with traditional monitoring of other operating parameters such as temperatures, pressures, RPM, etc. adds a new dimension to the monitoring of critical operating machinery and structures.

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