Structural Health Monitoring System (SHMS) for Bridge with Hybrid Sensor System

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Key words: GPS, Structural Dynamics Model Validation, Damage Identification, Structural Health Monitoring (SHM)

SUMMARY

The validation techniques applied in civil engineering is relatively less ripeness. We try to apply the validation technique that was proved effective in mechanical and aerospace engineering fields to large civil structures and build a reliable finite element model of civil structures, such as large bridges. The model can be used to detect the health status, monitor the deformation, and forecast the potential risk of structures.

To realize proposed system, we need to develop a structural health monitoring system (SHMS), together with a feasible data collection tools to gather experimental data from actual operational structure. As one of the feasible data collection tools for modal testing, GPS has been employed with other sensors by the IESSG at The University of Nottingham to acquire experimental data of large structure, such as deformations, velocity, acceleration, frequency, etc.

In this paper validation methods and damage identification approaches coupled with prototype of hybrid sensor system that composes a Structural Health Monitoring System (SHMS) is introduced. Data collected from a test bed bridge are processed and analyzed to demonstrate the feasibility of proposed SHMS. The results demonstrate that it is possible to achieve 3D millimetre positioning precision for detecting high dynamic structural deformations. The algorithms and field testing can be used to obtain a highly reliable finite element model for the purpose of SHMS.

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1. INTRODUCTION

The development of fast digital computers, numerical simulation techniques and measurement technology has led to successful structural dynamics model validation in the mechanical and aerospace engineering communities. Validation techniques combine finite element model of structure with experimental data of an operational structure, finding a reliably updated finite element model of this structure through comparison and refinement of the finite element model on the basis of experimental results. The reliable updated finite element model of actual structural can be used to further analysis and precisely forecast the characteristics of structure in the practical circumstance.

The validation techniques used in the mechanical and aerospace engineering fields consists of five procedures: data acquisitions, test planning, experimental testing, correlation, error location and updating. These procedures combine together to generate a reliable updated finite element model.

The validation techniques applied in civil engineering is relatively less ripeness. We try to apply the validation technique that was proved to be effective in mechanical and aerospace engineering fields for large civil structures and build a reliable finite element model of this structure, such as a bridge. The model can be used to detect the damage, monitor the deformation, and forecast the potential risk of structures.

To realize proposed system, we need to develop a structural health monitoring system (SHMS), together with a feasible data collection tool to gather experimental data from an operational structure. As one of the feasible data collection tools for modal testing, GPS has been employed with other sensors such as by the IESSG at the University of Nottingham to acquire experimental data of large structure, such as deformations, velocity, acceleration, frequency etc.

In this paper, the basic ideas of validation method and damage identification methods are introduced. The outline of a SHMS that based on the prototype of hybrid sensor system combing validation method and damage identification methods is describe. Data collected from a test bed bridge are processed and analyzed to demonstrate the feasibility of proposed SHMS. The results demonstrate that it is possible to achieve 3D millimetre positioning precision for detecting high dynamic structural deformations, and that can be used to obtain a highly reliable updated finite element model for the purpose of SHMS.

2. A HYBRID SENSOR SYSTEM

Over the last couple of years, different hybrid sensor systems have been investigated at the IESSG of the University of Nottingham. Initially, the research focus was on the expansion of the measurable sampling rate to detect higher structural dynamics. The research then evolved to develop a system which can be used to identify both small and large dynamic deformations with millimetre 3D positioning precision. Both systems are compared in the following sections, using sample data sets collected from bridge trials [1-3].

3. VALIDATION METHODS FOR STRUCTURES

Validation techniques combine the numerical simulation of structure, in general using finite element model, with experimental testing data from an actual structure, collected by various sensors, such as GPS sensors, to conduct comparison and refinement of the finite element model.

Validation techniques consist of several components. One important part of model validation process is test planning which has emerged in the last few years as a precondition for successful correlation. Test planning is a process of determining the optimum test parameters such as suspension, excitation and measurement locations on the basis of preliminary finite element predictions before commencement of the actual test. For aerospace industry, there some research about test planning has been processing, but for large and complex civil structure, such as long span bridge, almost no research has be conducted about test planning. Clearly, the result of test planning is dependent on the very model which is being validated and, as such, carries some uncertainties which have to be resolved during the validation process. For large complex civil structure, the only practical exciting method is ambient vibration testing (AVT), so the determination of measurement locations is the major concern. The complexity of the civil structures makes the test planning an extremely difficult problem since it relies on a model which may have any kinds of errors and uncertainties.

Correlation is a process of comparison of the dynamic properties between two datasets. Although correlation is described as a comparison process, essentially it is more than a simple comparison and in reality it is also a process of assessment of the results of test planning and the global completeness of experimental data sets. Correlation is probably the most mature area of model validation process. The most fundamental form of correlation is a comparison between mode shapes using Modal Assurance Criterion (MAC) introduced by Allemang and Brown in [4].

The simplest and most common definition of model updating is "adjustment of the finite element model on the basis of modal test results in order to minimize the discrepancies between theoretical and experimental behaviour of a structure" [5].

For damage identification of large and complex civil structures, the main advantages of an efficient model updating method is that the initial finite element model can be updated to match the experimental modal parameters, such as frequencies and mode shapes form large amount of data received from GPS sensors with 3D millimetre positioning precision. This updated model can then be used for detection of damage of the monitored civil structure.

3.1 Basic Theory of Validation Methods

In the following section, we give a simple preview of the theory background related to validation methods. A general finite element model can be expressed as following [6, 7]:

Assume that a finite element consists of n_e nodes, the corresponding coordinates and displacements at those nodes are x_i and u_i, then the coordinates x and the displacements u of interior points can be expressed as following:

$$x = \sum_{i=1}^{n_e} x_i N_i \quad (1)$$

$$u = \sum_{i=1}^{n_e} u_i N_i \quad (2)$$

where N_i is the shape function.

Assume that the shape functions are defined in a local coordinate system, the general formulation of the structural mass and stiffness matrices of a finite element can be expressed as follows:

$$M_e = \int_{-1}^{1}\int_{-1}^{1}\int_{-1}^{1} [N]^T \rho [N] \det(J) d\xi_1 d\xi_2 d\xi_3 \quad (3)$$

$$K_e = \int_{-1}^{1}\int_{-1}^{1}\int_{-1}^{1} [B]^T [D][N] \det(J) d\xi_1 d\xi_2 d\xi_3 \quad (4)$$

Where $[N]$ is the shape function matrix.
$[B]$ is the derivative of the shape function matrix.
$[D]$ is the matrix of material constants.
$[J]$ is the Jacobian matrix between the global and a local element coordinate system.

The global mass and stiffness matrices are obtained by assembling mass and stiffness matrices of the individual elements at the common nodes and can be expressed as following:

$$M = \sum_{i=1}^{n_{elem}} M_e \quad (5)$$

$$K = \sum_{i=1}^{n_{elem}} K_e \quad (6)$$

Where n_{elem} is total number of elements.

The equation of motion for a structural system which has N degrees-of-freedom and considering general viscous damping can be expressed as the following form:

$$M\ddot{u} + C\dot{u} + Ku = f \qquad (7)$$

Since it is very difficult to model damping accurately, different forms of damping can be assumed in order to simplify the analysis, but in most cases damping can be excluded when natural frequencies and mode shapes are calculated so that we express the equation of motion as following:

$$M\ddot{u} + Ku = f \qquad (8)$$

Considering the homogeneous part of the equation (8) and assuming a harmonic response of the following form:

$$\{x(t)\} = \{\phi\}e^{i\omega t} \qquad (9)$$

We can obtain the generalized form of the eigen problem. It can be written in the form

$$(K - \omega^2 M)\{\phi\} = \{0\} \qquad (10)$$

From above equation, we can express the eigen problem as standard form:

$$\det(K - \omega^2 M) = 0 \qquad (11)$$

We can solve the above eigen problem and obtain N values of the natural frequency as $\omega_1, \omega_2, ...\omega_N$

We simply substituted $\omega_1, \omega_2, ...\omega_N$ back into equation (10) to obtain the mode shapes, $\{\phi_1\}, \{\phi_2\}, ...\{\phi_N\}$ (also called normal modes), which describe the deformation shapes of the structure when it vibrates at each of the corresponding natural frequencies.

It can be shown that the mass normalized mode shapes satisfy the orthogonality conditions with respect to mass and stiffness matrices as defined in the following expressions:

$$[\phi]^T M[\phi] = I \qquad (12)$$

$$[\phi]^T K[\phi] = diag(\omega_1, \omega_2, ...\omega_N) \qquad (13)$$

The above orthogonality conditions play important rule for correlation and updating.
Assume that external force take the following harmonic form:

$$\{f(t)\} = \{F(\omega)\}e^{i\omega t} \qquad (14)$$

The steady-state response of a structure can therefore take the following form:

$$\{x(t)\} = \{X(\omega)\}e^{i\omega t} \qquad (15)$$

Assume that damping matrix take the structural damping, equation (7) can be rewrite as following:

$$M\ddot{u}(t) + iD\dot{u}(t) + Ku(t) = f(t) \qquad (16)$$

After substitution of equation (14, 15) into the equation of motion, (16), we can get the following expressions:

$$(-\omega^2 M + iD + K)\{X(\omega)\}e^{i\omega t} = \{F(\omega)\}e^{i\omega t} \quad (17)$$

$$\{X(\omega)\} = [\alpha(\omega)]\{F(\omega)\} \quad (18)$$

$$[\alpha(\omega)] = (-\omega^2 M + iD + K)^{-1} \quad (19)$$

$\alpha(\omega)$ is the reacceptance matrix of the system, whose general term $\alpha(\omega)_{j,k}$ can be written as a function of the natural frequencies and mode shapes of the system in the following form:

$$\alpha(\omega)_{j,k} = \sum_{i=1}^{N} \frac{\phi_{j,i}\phi_{k,i}}{\omega_i^{\,2} - \omega^2 + i\eta_i\omega_i^{\,2}} \quad (20)$$

Assuming that the system is being excited at a frequency, which is equal to the natural frequency of mode ϕ_i and ω_i, and considering only the most significant term in the series in expression (20) , we obtain the following:

$$\alpha(\omega_i)_{j,k} \approx \frac{\phi_{j.i}\phi_{k,i}}{i\eta_i\omega_i^{\,2}} \quad (21)$$

Taking above equation into equation (15), we can obtain the following:

$$X(\omega_i) \propto \frac{\phi_{j.i}\phi_{k,i}}{i\eta_i\omega_i^{\,2}} \quad (22)$$

Considering equation (15), we can get the displacement, velocity and acceleration, respectively, as the following:

$$\{x(t)\} = \{X(\omega_i)\}e^{i\omega_i t} \quad (23)$$

$$\{\dot{x}(t)\} = i\omega_i\{X(\omega_i)\}e^{i\omega_i t} \quad (24)$$

$$\{\ddot{x}(t)\} = -\omega_i^{\,2}\{X(\omega_i)\}e^{i\omega_i t} \quad (25)$$

Substituting (22) into the expressions for displacement (23-25), we can obtain the following relationships for vibration amplitudes of these quantities:

Displacement Amplitude $\propto \dfrac{\phi_{j.i}\phi_{k,i}}{\omega_i^{\,2}}$ (26)

Velocity Amplitude $\propto \dfrac{\phi_{j.i}\phi_{k,i}}{\omega_i}$ (27)

Acceleration Amplitude $\propto \phi_{j,i}\phi_{k,i}$ (28)

Based the above three relationship, various validation techniques can be deduced and form the basic equations for validation method.

Finite element model that has update through measurement data and match well experimental data is backbone for VBID technique. It can used to finding optimal placement of sensor for monitoring the structure, to reducing the number of degree of freedom in the FEM to match the experimentally measured degree of freedom, to selecting the subset of identified lower structural modes that may be used for SHM and damage identification.

4. DAMAGE IDENTIFICATION METHODS FOR STRUCTURES

Health monitoring of structures and the detection of damage at the earliest possible stage have become important issues in almost all area of application, ranging from aerospace to civil engineering. Success in damage identification depends mainly on the sensitivity of sensors used, the accuracy of test-based modal parameters and reliability of interpretation algorithms.

Structural Health Monitoring (SHM) using Vibration Based Damaged Identification (VBDI) procedure depends on an optimal integration of experimental, analytical and information system components. These components include: Experimental identification of the structural modal characteristics through modal testing; an efficient damage identification algorithm to relate sensor measurements to the physical changes.

Beside the VBDI methods, there are other technologies: Non-destructive Evaluation Methods (NDE), such as ultrasonic and acoustic methods, and Vibration Based Damaged Identification methods. The conventional NDE methods depend on direct measurements to determine the physical condition of the structure and to evaluate its reliability. In addition this methods require that the vicinity of the damage is known in advance and portion of the structure being inspected is easily accessible. Those requirements are not impractical for inspecting large civil structures. The need for more generalized and more suitable for large civil structures damage identification methods that do not rely on prior knowledge of damage location and can be applied to large and complex structures has led to the development of Structural Health Monitoring system that use VBDI methods. The VBDI methods rely on the measurement of change in the vibration characteristics of the structure and the periodic measurement of those characteristics while the structure is in service. The accuracy of the data acquired from the sensors is crucial key for success of VBDI technique. Success in damage identification depends mainly on the sensitivity of sensors that employed to receive the measurement data, the accuracy of the test-based modal parameters and the reliability of interpretation algorithms. These model parameters, including frequencies, mode shapes and modal damping, are functions of the physical properties of structure, including stiffness, mass and damping matrices. Therefore, any change in these parameters can be used as an indicator of the overall integrity of the structure and a means of finding the location and extent of damage.

VBDI based methods have many advantages, two main describe as following: One advantage is that the location of damage does not need to be known in advance, so the GPS sensors that measure the vibration characteristics need not to be placed in the vicinity of damage. A limit number of GPS sensors can provide vital information that would allow identification of damage, even for large and complex civil structure, such as large span bridge.

A major shortcoming of the most existing techniques that depend in modal update procedures is that comparison of post-damage structural modes with these of the pre-damage modal often requires the solution of non-linear optimization problems. When applied to large and complex structures, these methods can sometime lead to ambiguous results. The problem of identification of damage location and extent based on the changes in global vibration characteristics determined from measurements at a limited number of response locations can be formulated in terms of an under-determined system of non-linear equations implying that there are more unknown than the number of equations. The solution of such mathematical problem is non-unique. Advanced and complex mathematical techniques need to be employed to solve the non-linear optimization problem. This is an area currently ongoing research. In fact, there are almost no existing software optimizers that can handle the identification of a global minimum result and need long time to complete the computations of process, especially when the objective function to be minimized contains a large number of design variables.

There are a number of limitations associated with vibration-based damage assessment. . One is that these vibration-based damage identification technique would be successfully if the damage results in a degradation of the stiffness of structure, so they can not applied detection of damage that cause no or few stiffness degradation that issue may take place in practical civil structure.. Another limitation is that the VBDI technique my not fully successful when the damage results in nonlinearity in structure.

There are some important factors that may effect on these techniques successful application in complex civil structure, such as sensitivity of global response to damage, optimal selection of response and excitation placement and finite element modelling complexity of mathematical identification algorithm.

For damage of in service structure, we have the classification system defines four levels of damage identification [7]:
Level1: Determination that damage is present in the structure;
Level2: Level1 plus determination of the geometric location of the damage.
Level3: Level2 plus quantification of the severity of the damage.
Level4: Level3 plus predication of the remaining service life of the structure, or in other words how reliable the structure is in serving its normal loading function.

4.1 Theoretical Background of Damage Identification Method

It is assume that damage is quantified by a local decrease of stiffness, which affects the model parameters, including frequencies and mode shapes, of the monitoring structure. The equations of motion that governing the free vibrations of an undamped n-degree of freedom system are [7, 8]

$$M\ddot{u} + Ku = f \qquad (29)$$

where M is $n \times n$ mass matrix, K is $n \times n$ stiffness matrix and u is a vector of nodal displacements. M and K are positive definite matrix. The associated eigenvalue problem is given as following:

$$(K-\lambda_i M)\varphi_i = 0 \tag{30}$$

$$\lambda_i = \sqrt{\omega_i} \tag{31}$$

Where ω_i is the natural frequency, φ_i is the corresponding mode shape of the structural system. We assume that the φ_i have normalized, so we have the following:

$$\varphi_i^T M\varphi_j = \delta_{ij} \tag{32}$$

In general case, we can realize that damage in the original structure causes a change in the stiffness matrix by an amount δK and we assume that damage not cause any change in the system mass matrix. The change in the system stiffness matrix leads to change $\delta\lambda_i$ in the i^{th} eigenvalue and $\delta\varphi_i$ in the i^{th} eigenvector. The eigenvalue problem of the damaged structure is then given as following:

$$[K+\delta K-(\lambda_i+\delta\lambda_i)\cdot M][\varphi_i+\delta\varphi_i] = 0 \tag{33}$$

Considering the equation (30), we expand and obtain following:

$$(\delta K-\delta\lambda_i M)\varphi_i + (K-\lambda_i M)\delta\varphi_i + (\delta K-\delta\lambda_i M)\delta\varphi_i = 0 \tag{34}$$

We make multiplication the both side of equation by φ_i^T, and obtain following:

$$\varphi_i^T(\delta K-\delta\lambda_i M)\varphi_i + [(K-\lambda_i M)\varphi_i]^T\delta\varphi_i + \varphi_i^T(\delta K-\delta\lambda_i M)\delta\varphi_i = 0 \tag{35}$$

Considering equation (30), we can simplify as following:

$$\varphi_i^T(\delta K-\delta\lambda_i M)\varphi_i + \varphi_i^T(\delta K-\delta\lambda_i M)\delta\varphi_i = 0 \tag{36}$$

We assume that $\delta\varphi_i$ can be expressed as following:

$$\delta\varphi_i = \varphi_{id} - \varphi_i \tag{37}$$

where φ_{id} is the corresponding i^{th} mode shape of the damaged structural system.
Considering equation (30), we get following:

$$\varphi_i^T\delta K\varphi_{id} = \delta\lambda_i\varphi_i^T M\delta\varphi_{id} \tag{38}$$

These equations (38) relate the unknown change in stiffness matrix δK and changes in modal parameters $\delta\lambda_i$.

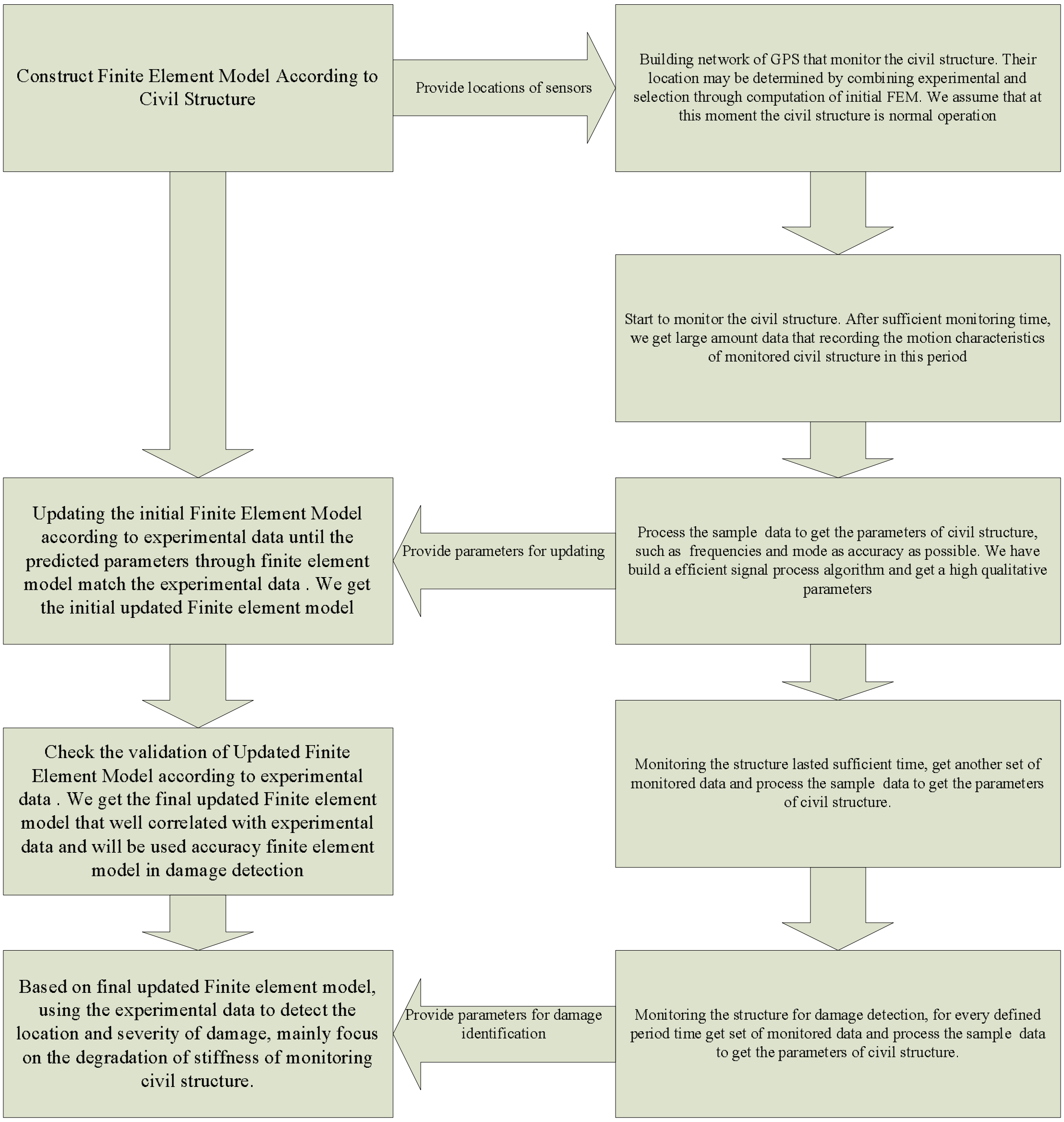
Since M is the original mass matrix and is not change and known in advance, if we assume that the damage would result in a small δK, the higher order terms in equation (36) can be neglected ,we obtain the following:

$$\delta\lambda_i = \varphi_i^T\delta K\varphi_i \tag{39}$$

These two equations (38, 39) form the bases for this SHM process. They can be used as constrain in a non-linear optimal computation for damage identification [9].

5. THE OUTLINE OF STRUCTURAL HEALTH MONITORING SYSTEM (SHMS)

Based on the previous methods and technologies, we describe the outline of a Structure Health Monitoring System as following. The all methods and techniques are complex and ongoing research area, so we can only give some minds that may be useful for constructing the SHMS. The flowchart of SHMS is given as following:



Outline of Structural Health Monitoring System

6. CONCLUSIONS

Construction of a successful Structural Health Monitoring System (SHMS) face many difficult and may be take a long time to obtain practical SHMS. GPS technology, Validation and damage identification consist of the main component of SHMS. We have given preview about the three main component and provide an outline of SHMS.

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