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A BENCHMARK PROBLEM FOR STRUCTURAL HEALTH MONITORING

The importance of developing robust monitoring systems that can detect and locate progressive deterioration in structures or abrupt damage induced by extreme loading events is well recognized in the aerospace, mechanical, and civil engineering communities. In the case of civil structures, such as buildings, bridges, off-shore platforms or dams, the most commonly utilized approach for SHM (structural health monitoring) is periodic visual inspections. Needless to say, this approach is limited to deterioration or damage that is not hidden from view and it can be expensive. In certain cases, visual inspections are complemented by non-destructive testing procedures but these are local in nature and can not provide information on the overall health of the structural system.

A good example of the limitations of SHM technology based on visual inspections or localized tests is found in the damage induced by the 1994 Northridge Earthquake on welded moment-resisting connections of steel buildings. In particular, many steel structures in the area of strong shaking suffered fractures of the welds in the connections that framed beams into columns with no distress apparent from an overall inspection. Needless to say, given the cost and difficulty of inspecting hidden structural elements and connections, detailed inspection (removal of partitions and so on) was not carried out at first. It was in fact only when weld fractures were identified in buildings under construction (and thus where the connections were not hidden) that detailed inspection of existing structures showed that the type of weld fractures that had been observed was pervasive in the existing building stock. The situation, if undetected, would have resulted in a significant number of weakened buildings that would pose undue risk to the occupants during future earthquakes.

An alternative to visual inspections and local tests that is being aggressively investigated in various engineering disciplines is that of structural health monitoring based on vibration signals. A typical SHM system consists of a set of motion sensors (e.g. accelerometers or fiber-optic strain gauges) distributed over the structure that communicate with a data acquisition system connected to a central processing unit that may be in an operator room. For remote real-time monitoring of structures, the processed data must be on-line, possibly through a dedicated line or via an Internet link.

The basic idea is well established—namely, the vibration characteristics of a system (mainly frequencies and mode shapes) that can be identified from the recorded motions are a function of the physical parameters (mass and stiffness). Therefore, changes in the physical properties from damage may be inferred from changes in the identified modal characteristics using suitable algorithms. Then, in theory, damage may be detected, localized and assessed through vibration monitoring.

This inverse problem, however, is a difficult one for which there is no well-established solution at present. An important part of the current effort to affect positive progress in SHM technology in civil engineering structures is the development of well-defined benchmark problems that allow comparison of the performance of various techniques for realistic conditions. This paper outlines the work associated with the definition of one of these benchmark structures.

THE DIFFICULTIES

Although most of the observations made in this section apply in general, the discussion is presented from the perspective of damage identification in civil engineering structures. The difficulties in identifying damage from vibration measurements can be readily recognizing by noting that:

a) Modal characteristics are rather insensitive to localized damage so the frequency and mode shape changes (for the level of damage that one is interested in detecting with a SHM system) are small.

b) Input signals are noisy and limited in frequency content so only a few lower modes are sufficiently excited to be identified. In many cases in civil structures, the input signals are unavailable (naturally-occurring ambient excitation is used).

c) Output signals are also corrupted by noise and, as noted, contain information on a restricted set of modes only (typically the low frequency modes). Also, the number of sensors is limited and so the spatial distribution of the motion is not known completely.

d) Changes in frequencies and mode shapes do not directly show what physical parameters have changed. An inverse problem must be solved, typically by updating a structural model so that the analytical modal characteristics match (or closely approximate) the measured ones. Because the mathematical model never captures the true complexity of the real system, the updated model can match the modal data but the updated parameters may not be well-correlated with those in the true damaged system.

Vibration-based damage identification, therefore, is made difficult by the fact that the technology requires that one extract subtle information that is embedded in imprecise and incomplete data and map it to physical changes using models that, inevitably, are also imprecise and incomplete.

Many techniques have been proposed to circumvent or minimize the problems that derive from the limitations in the measured data and the model, and the assumptions used to establish these techniques vary widely. In many cases the difficulty in applying a technique that works well in theory to a real structure lies in the fact that the results are sensitive to one or more assumptions which in practice are not entirely satisfied. For example, a technique developed on the premise that the mass matrix is diagonal and is known without error may perform well in simulations but fail when applied to a real structure where these conditions are never truly satisfied. A related but distinct issue that has also hindered practical implementation of several techniques is lack of scalability. Methods that characterize damage by inspecting changes in the matrices of a second order formulation (mass, damping and stiffness), for example, often work well in problems of academic interest but are nearly impossible to apply when the number of degrees of freedom is large.

IASC-ASCE TASK GROUP ON SHM

A conclusion in the previous discussion is that progress in the transfer from research to practical application in the field of SHM has not been entirely satisfactory. Perhaps what has hindered real progress the most is the lack of accepted full-scale international benchmark problems that define realistic conditions and allow direct comparisons between the performance of various algorithms.

Efforts to address this situation where initiated by members of the research community at the 1996 International Workshop on Structural Control (Chen, 1996). In particular, a draft plan for forming task groups to study the problem of SHM was prepared during this meeting. The agreement reached was to form three task groups, one for Europe, one for Asia and one for the US. The US task group eventually solidified in 1999 under the joint auspices of the International Association of Structural Control (IASC) and the Dynamics Committee of the American Society of Civil Engineers (ASCE). The first meeting of the IASC-ASCE Task Group took place during the 13th ASCE Engineering Mechanics Conference at Johns Hopkins University, Maryland, in 1999.

As it was anticipated from the discussions that had taken place since the First Workshop on Structural Control, the US task group decided to focus their first efforts on preparing a well-defined benchmark problem. Keeping in mind that credible SHM technology must be shown to work with real data, it was decided to select a benchmark problem for which a physical model was available.

THE BENCHMARK STRUCTURE

The structure selected for the first benchmark problem is the four-story 2-bay by 2-bay steel braced frame depicted in Fig.1.

Fig. 1 The benchmark test structure

The structure has a 2.5m × 2.5m base, is 3.6m tall and is located at the Earthquake Engineering Research Laboratory of the University of British Columbia (Ventura et.al. 1997). The elements that conform the structure are hot rolled grade 300W steel (nominal yield stress 300 MPa [42.6 ksi]) and are of unusual dimensions, designed for a 1/3-scale model with the properties listed in Table 1. In addition to the main members, horizontal bracing at each floor level is included to ensure effective diaphragm action in the absence of a concrete floor. The mass of the structure is made up of the self-weight of the members plus added masses that are also listed in Table 1.

Table 1: Properties of structural members

Property	**Columns**	**Beams**	**Braces**
Section Type	B100×9	S75×11	L25×25×3
Cross sectional area [$\times 10^{-3} m^2$]	1.133	1.43	0.141
Moment of inertia: [$\times 10^{-6} m^4$]			
Strong *dir* Weak *dir*	1.97 0.66	1.22 0.25	0 0
Torsion constant [$\times 10^{-9} m^4$]	8.01	38.2	0
Modulus of elasticity (Pa)	2×10^{11}	2×10^{11}	2×10^{11}
Mass per unit length [kg/m]	8.89	11.0	1.11

Slab masses	1	2	3	4
[kg]	3200	2400	2400	1600

Although some issues encountered in full size buildings are not included in the benchmark definition (non-structural elements and potential soil-structure interaction being the most evident), the benchmark does contain a significant degree of realism. Indeed, in some items, like the flexibility of the connections, the difficulties to characterize the benchmark may exceed those found in the corresponding full-size structures. In any event, the task group weighed the advantages and limitations and concluded that a first benchmark problem based on a physical model that could be tested for various simulated damage cases was appropriate for the first phase of the research.

To gain an appreciation for the characteristics of the benchmark structure, the frequencies of the first two translational modes and the first torsional mode, identified experimentally by Black et.al (1998) in tests carried out in 1997, are listed in Table 2.

Table 2 Experimental Frequencies

	X_1	Y_1	T_1
Frequency (Hz)	8.42	7.80	11.11

RESEARCH ON THE BENCHMARK USING SIMULATED DATA

A resolution reached during the first meeting of the IASC-ASCE task group was that an analytical research phase was appropriate prior to initiating the SHM research using experimental data. In particular, it was felt that research using simulated data would allow a good introduction to the structure and allow time to explore techniques and polish algorithms prior to facing the full complexity of experimental results.

The work for the analytical portion of the research was defined in a series of cases where three aspects are varied:

a) the damage scenario
b) the true model used to generate the simulated data
c) the information assumed available to the user.

The damage scenarios where not necessarily intended as realistic but where chosen so that the damage identification became progressively more difficult as the index used to define the damage pattern increased from 1 to 5. Damage pattern 1(DP-1), for example, involves loss of stiffness of all the braces in the first level while DP-5 is defined as loss of stiffness of only one brace in each of 1st and 3rd stories plus one loosen beam connection in level 1. Details of the damage patterns may be found in Johnson et.al. (2000), or at the web site of the SHM task group *wusceel.cive.wustl.edu/asce.shm*/

To gain some appreciation for the importance of the mismatch between the mathematical model and the actual structure (which is unavoidable when real data is used), two models for generating the simulated data were developed. The first is a crude 12-DOF model obtained by assuming that the floor slabs are rigid in and out of the plane.

The second model has 120 DOF and is obtained by allowing 6 DOF per joint and imposing the rigidity of the diaphragm only in the horizontal plane. The participants in the study whose techniques demanded a mathematical model of the system were required to use only a 12-DOF model (based on rigid horizontal floors) in the damage identification. Needless to say, when the data was generated with the 120-DOF model, there is mismatch or modeling error in the analysis. It is important to emphasize that the 12-DOF model that the participants where asked to use was not to be the best approximation possible, but rather a purposely poor representation based on full rigidity of the floor system. The idea, of course, was to ensure that the mismatch between the damage-detection model and the true model was significant.

The third and last item varied in defining the agenda for the analytical phase of the work was the information available to the analyst. In particular, cases with known and unknown force input were defined, as well as cases with full and partial sensor data. In all the cases of simulated data, additive sensor noise was included in the analyses.

RESULTS

The results obtained by the participants in the analytical phase of the study are currently being organized and will be reported in detail in a refereed journal. A preliminary examination has shown, however, that the participants where, for the most part, successful in identifying and locating the simulated damage cases that were defined. As expected, difficulties were most significant when the damage is modest, the sensor data is limited and the force input is unmeasured.

EXPERIMENTAL PHASE

The tests to collect the data for the experimental phase of the work on the benchmark structure were carried out in the summer of 2000. The data has now been organized and placed on the web site of the SHM task group for the use of anyone interested. In addition to the vibration signals, all the data on the dimensions of the structure, the location of the sensors, etc., has also been made available at the web site. The analysis of these data has just recently been started and the first meeting to discuss the progress of the participants will take place in June of 2001 at the joint ASME-ASCE conference to be held in San Diego.

CONCLUDING REMARKS

A task group consisting of a dozen or so active members has defined a benchmark for structural health monitoring consisting of simulated-data cases and experimental cases. The models and data are available for the research community to download at the web site of the task group at wusceel.cive.wustl.edu/asce.shm/.

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