Damage Assessment of Complex Structures from Transient Dynamic Response

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Abstract

Damage detection and assessment algorithm using transient dynamic response is developed for complex structures. A parametric system identification method is implemented in the algorithm as the main tool to identify a structural system. A nonlinear constrained optimization problem is solved for estimating optimal structural parameters. To localize damaged members, the adaptive parameter grouping scheme is applied. To assess the severity of damage statistically, the time windowing technique is applied. Main considerations in developing the algorithm are noise and sparsity in the measurements. A simulation study is carried out with a truss structure excited by a harmonic force.

Introduction

A structure can be easily exposed to various types of loading, that may cause serious damage in the structure and eventually lead to its failure. Regular inspection and evaluation of existing structural systems have been increasingly demanded. Visual inspection has been used as the most classical option but provided very limited information of the condition of a structure. Currently, non-destructive testing methods for evaluating structures have been widely applied with field measurements to augment the classical approach. In the present paper, non-destructive methods do not indicate local NDT methods such as ultrasound but rather can be classified as a method of inspecting a structure globally by vibrating it and measuring its response.

System identification methods have been widely applied in various structural engineering fields to verify structural models or to detect damage in structural systems. A system identification method requires sets of measured response of the structural system and a parametric or non-parametric model for the structure. We use a parametric finite element model with system parameters of mass, damping, and stiffness properties, and apply an optimization technique to estimate optimal values of the parameters and to assess damage.

Most of the system identification algorithms have been developed by using frequency-domain data transformed from time-domain row data.[3,5] The biggest advantage of using the frequency-domain data may be the easiness of handling them in a system identification algorithm. Regardless of the amount of measured time-varying row information, after the data is transformed into a frequency set, the algorithm can deal with only the identified modal data. However, the counterpart disadvantage is the fact that only limited modal information usually can be generated in the frequency domain. The discrepancy between the number of identified modes and that of degrees of freedom of the model is usually considerable.

The applications of time-domain system identification methods for structural engineering problems have been relatively limited so far, even though its development seems to be well-established in other engineering applications such as control theory.[2] The limitations can be easily demonstrated from the example studies, where the number of degrees of freedom in a structural model was small. In most of the applications, the measurements were assumed to be complete in all the state vectors of acceleration, velocity, and displacement. However, in reality, the measurements usually are incomplete in state and space. Only acceleration or displacement can be measured at selected degrees of freedom in a structure. The deficiency becomes serious as a large structure is considered. In spite of the limited applications of the time domain system identification methods, the algorithms seem to be very attractive because wealth of data can be always obtained from the history of measured response, and because experiment and data acquisition are easier than those for static and modal responses. The only problem in applying the meth-

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ods seems to be the burden of computation in dealing with huge amount of data.

System identification with transient dynamic response

The governing model for a structural vibration under transient dynamic loading can be described by dynamic equilibrium equation of Eq.(1).

$$M(x)\ddot{u}(t) + C(x)\dot{u}(t) + K(x)u(t) = f(t) \quad (1)$$

Each structural matrix is defined with the parameter vector $x=\{x_M\, x_C\, x_K\}^T$, where x_M, x_C, x_K are mass, damping, and stiffness parameters, respectively. The parameters should be decomposed from the structural matrices before being evaluated in the parameter estimation process.

A system identification method directly using this differential equation was introduced by Hjelmstad *et al.*[1] If the geometry and topology of the structure, and load history are assumed to be known, the first step is to compute a complete set of the state vectors from sparse measured response. Then, we need to estimate optimal structural parameters. If we could measure accelerations at all the degrees of freedom in the structural model, we can generate the other state vectors by simple numerical integration. However, since it is almost impossible to measure acceleration at all the degrees of freedom, we have to compute or assume the unmeasured parts of all the three state vectors before estimating parameters.

Generally three different schemes can be considered to overcome this sparsity problem; *i.e.* (*a*) reduction of the structural model, (*b*) expansion of the measured response into the unmeasured degrees of freedom, and (*c*) idea of considering the unmeasured parts of the state vectors as additional unknowns. Among them, the first scheme with a reduced finite element model for a structure should not be applied if it is required to locate damage precisely. The second scheme of data expansion has been widely applied for frequency-domain system identification methods, but no single example is available for time-domain system identification methods from our review. Also, the problem in applying the third scheme is due to the fact that the amount of unmeasured responses increases rapidly as time step adds up but the number of unknown parameters does not change. Hjelmstad *et al.*[1] proposed some possible ways of assuming the unmeasured state vectors at each time step.

If we consider the unmeasured state vectors as additional unknowns at each time step, we can solve the following nonlinear constrained optimization problem of Eq.(2) to estimate optimal parameter values.

$$\text{Minimize } J(x,\bar{U}) = \frac{1}{2}\sum_{k=1}^{ntp} \alpha_k \left\| M(x)\ddot{u}_k + C(x)\dot{u}_k + K(x)u_k - f_k \right\|^2$$
$$\text{subject to } \underline{x} \le x \le \bar{x} \quad (2)$$

where $\underline{x}, \bar{x}$ are the upper and lower bounds for the unknown parameters, *ntp* is the number of time points, and $\bar{U}$ represents the collection of responses at the unmeasured degrees of freedom from *ntp* time points. Since velocity and acceleration can be expressed by the displacement terms in the difference methods, the unknowns in $\bar{U}$ can be displacements only.

Damage detection and assessment

Damage can be defined as the reduction in structural parameters from their baseline values between two separated time inferences, which affects the structural performance in carrying loads and in controlling vibration of structures. For the damage detection and assessment, most of the available applications of the system identification methods have been limited with static or modal responses. The time-domain system identification methods available in the literature also have been only applied for verifying structural models without any attempt to extend the algorithms to damage detection and assessment.

To detect damage in a complex structure, we are required to develop a scheme to localize damaged areas precisely within a provided finite element model for the structure. The adaptive parameter grouping scheme can be applied for that purpose. Starting from the baseline parameter grouping case, parameter groups can be subdivided sequentially until all the damage can be localized. During updating the parameter groups, the defined finite element model need not be modified and only the structural parameter values can be changed. Couple of ideas of subdividing of parameter groups are available in the literature.[4,5] We implement a binary searching technique with minimizing the objective function value of Eq.(2).
After localizing damage, theoretically we can determine a damaged member in a structure by checking the reduction in the estimated parameter from the baseline value. However, since noise always ruins the measurements, the parameters should be evaluated with the consideration on noise. A member vibrating properly under applied load may provide a good estimation of its parameter. However, for some members insensitive to the applied load with negligible amplitude of vibration, it will be difficult to estimate their parameters correctly with noisy measurements. Since noise is random in nature, we need to evaluate the parameters statistically.[4] To obtain statistical properties for assessing damage from the estimated parameters, we apply the time-windowing scheme. With the

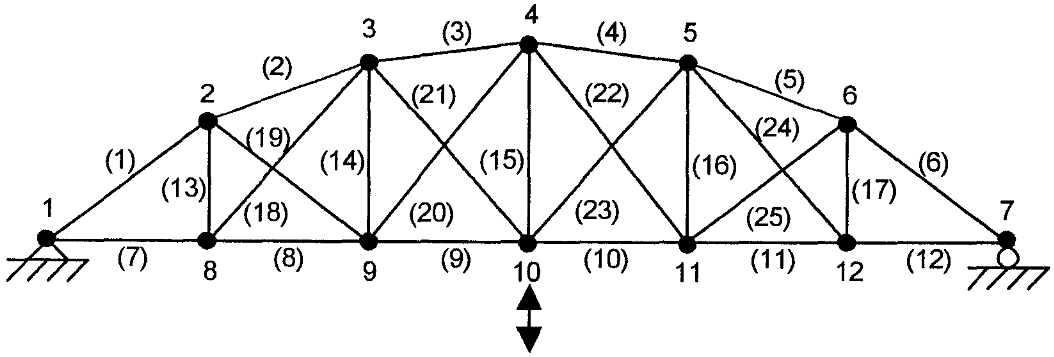

Fig. 1 : Geometry and topology of a Bowstring truss

data in each time window, the adaptive parameter group updating scheme can be applied and can generate an estimate of each element parameter. From a series of estimated values for an element parameter from a number of time windows, we can compute mean and standard deviation of each element parameter. The number of time windows should be large enough to yield statistically meaningful results. We define two damage indices with the computed mean and standard deviation values as follows.

$$bias\_cx_m = \frac{|\bar{x}_m - x_m^*|}{x_m^*}, \quad bias\_sd_m = \frac{|\bar{x}_m - x_m^*|}{\sigma_m} \tag{3}$$

where $\bar{x}_m, \sigma_m$ are mean and standard deviation computed from a number of time windows, and x_m^* is the baseline value of the *m*th parameter. Mean value may provide a good estimate of the parameter from noisy measurements and the standard deviation value may indicate the sensitivity of each member parameter. If a member vibrates less, its parameter is insensitive to the measured vibrational response and thus the resulting standard deviation of the parameter will be relatively large with noisy measurements.

Numerical simulation

A numerical simulation study is carried out with a simple bowstring truss structure to demonstrate the efficacy of the developed damage detection and assessment algorithm. The structure is composed of 25 members with 21 degrees of freedom as shown in Fig. 1. We assumed that the mass and damping properties are the *a priori* knowledge in the current simulation study. The baseline structure is assumed to be composed of four different sectional areas for upper, lower, vertical, and diagonal members. To simulate damage, we imposed 55% reduction in the sectional area of member (10).

We applied a sinusoidal load in the vertical direction as indicated in Fig. 1, and obtained the analytical time-domain response. The frequency of the sinusoidal force was adjusted close to the first vibrational frequency so that the truss could vibrate more to yield a better estimation of parameters. We assumed that accelerations are measured at all the degrees of freedom at each time step. To simulate field measurements, we added randomly generated noise to the analytically computed acceleration and computed velocities and displacements by the Newton-β method at the specified time points in each selected time-window. Then, the responses were applied to the developed damage assessment algorithm to detect and assess damage.

For the case study, we assumed measurement noise with the maximum amplitude of 6% proportional to the computed accelerations. We selected 50 non-overlapping time windows randomly from the measured transient response and computed mean and standard deviation values for each member. Each window contains a sufficient number of data points to provide a reliable estimation. The estimated parameters and two damage indices are drawn in Fig. 2. From the figure, we can observe that the actually damaged member (10) can be easily identified as the most severely damaged one. However, the other members also show a little reduced mean values from the baseline properties. It can be observed that the figures of two damage indices provide more clear information of locating the damaged member.

In Fig. 3, we compared the simulated measured acceleration and the identified history of acceleration in the vertical direction of node 9. To obtain the identified acceleration in the first figure (*a*), we modified only the sectional property of member (10) in the structure with the estimated value, which was slightly larger than the actual one. The second figure (*b*) was added to demonstrate the efficiency of the two damage indices. For the figure (*b*), the sectional properties of member (7)-(10) are modified with the estimated values. Members (7)-(9) were selected

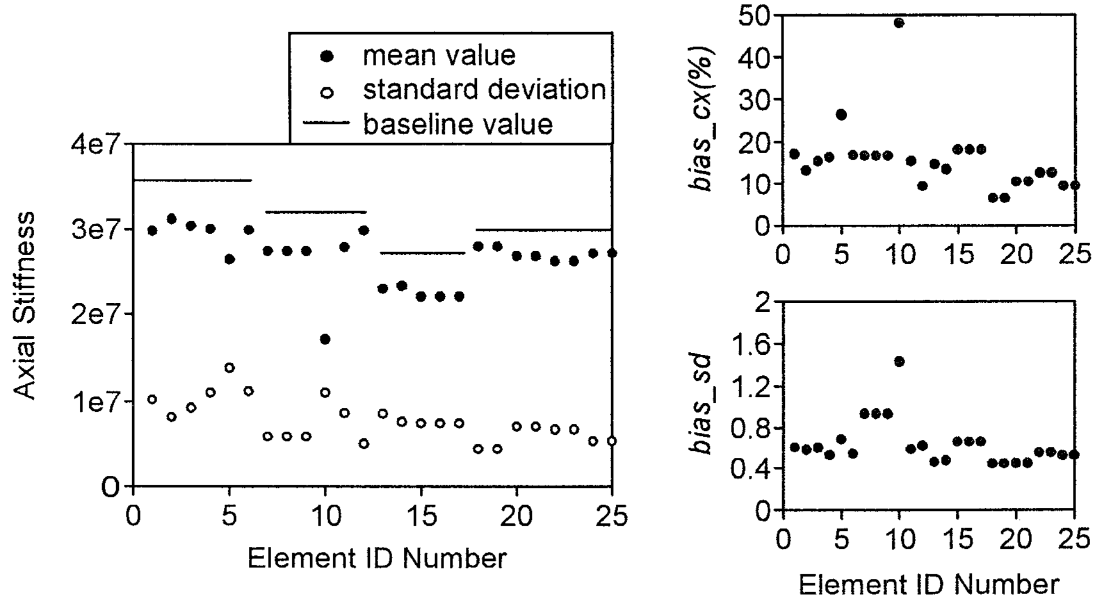

Fig. 2 : Estimated parameters and the computed damage indices

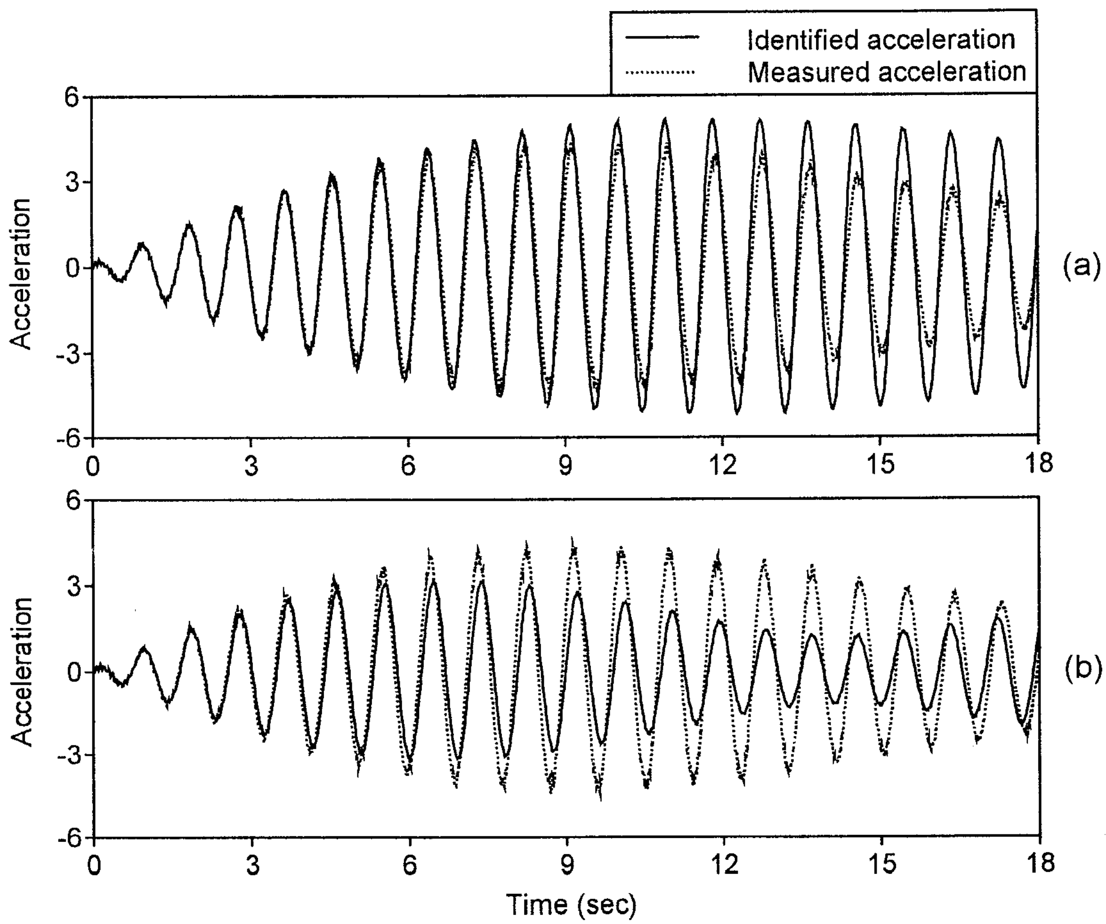

Fig. 3 : Comparison of measured and identified acceleration history in the vertical direction of node 9

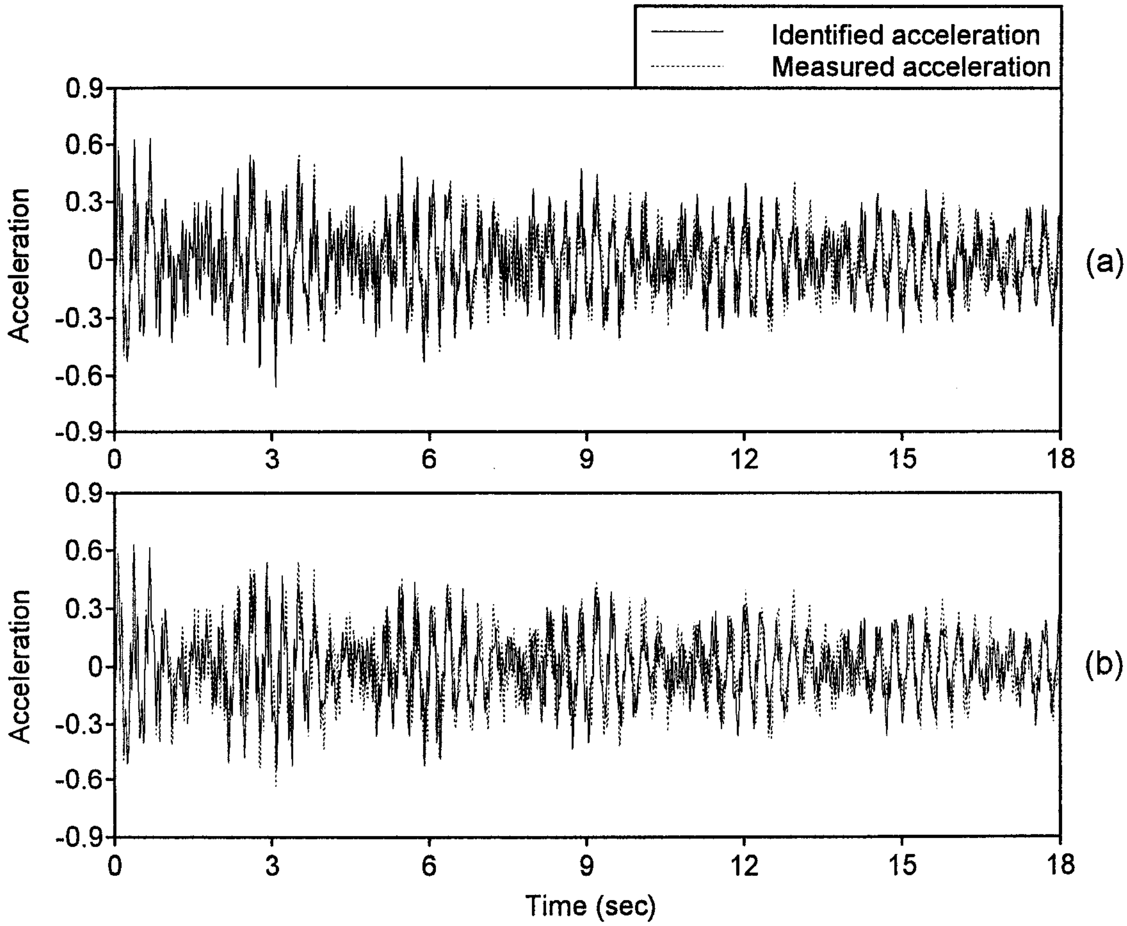

Fig. 4 : Comparison of measured and identified accelerations at non-resonant load frequency

additionally because the second damage index *bias_sd*'s were close to the value of 1.0.

From the figure (*a*) in Fig. 3, we can observe that the amplitude of identified acceleration becomes higher than that of the measured one as time step increases. However, the repeating periods of both curves almost coincide. In the figure (*b*) for the second case, the amplitude of identified acceleration becomes smaller rapidly than that of the measured one and the repeating periods do not coincide well as time step increases. The observations from the two figures indicate that the actual stiffness of the truss is weaker than the simulated first case with the reduced sectional area in member (10) but must be stronger than the second case with the reduction in members (7)-(10). In other words, damage is under-estimated in the first simulated structure, but over-estimated in the second. Also, the coincidence of the repeating period in the first figure strongly illustrates that member (10) may be the only damaged member.

When identified accelerations were compared with measured ones with a non-resonant frequency of applied load, the results are drawn in Fig. 4 for both cases of (*a*) and (*b*) with the same reduction in member sectional properties as for Fig. 3. Both figures in Fig. 4 show a good coincidence of two curves almost everywhere except some difference in the amplitudes. From the figures, we can also observe that the results do not much change by adding extra members (7)-(9), even though a discrepancy in the amplitudes is larger when the extra members are also considered as damaged. Therefore, we can conclude from the comparisons of Fig. 3 and Fig. 4 that it is highly required to apply a sinusoidal load resonant to the vibrating structure to detect and assess damage properly on a more reasonable basis.

Conclusion

A damage detection and assessment algorithm using measured transient dynamic response is introduced and tested with a simulated example. The simulation study with fully measured acceleration demonstrated the usefulness of the developed damage detection and assessment algorithm.

The constrained nonlinear optimization process usually requires a lot of iterations to minimize the objective function and the iterations are repeated at each subdivision with a newly defined parameter grouping. Even though repeated iterations require a lot of computation, the adaptive parameter grouping scheme and the use of time windowing scheme have been proved to be very useful and reliable for detecting and assessing damage.

The simulation study verifies the fact that the applied frequency of dynamic loads must be close to the natural frequency of the vibrating structure to obtain valuable information on damage. From the results of simulated damage cases, we could easily clarify the location and the severity of damage.

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