측정 가속도를 사용한 구조 손상 진단

Detection of Structural Damage from Measured Acceleration

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요지

구조물로부터 측정된 가속도 시간이력을 이용하여 구조 손상을 찾아내고 평가하는 기법을 제시하였다. 구조계의 손상을 찾아내는 알고리즘의 주요한 수단으로써 parametric system identification 방법을 사용하였고 매개변수화된 구조물의 최적 매개변수를 추정하기 위해 구속적 비선형 최적화 기법을 사용하였다. 손상된 부재를 분리하기 위한 방법으로서 적합적 매개변수 모음법을 적용하였고 손상의 정도를 통계적으로 평가하기 위하여 측정된 가속도 시간이력에 time window 기법을 적용하였다. 가속도 이력 측정에 있어서의 불충분성과 측정오차를 고려하여 알고리즘을 개발하였고, 조화진동하중으로 구조물을 가진하여 구조 손상을 진단하는 수치모의실험을 실시하였다.

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 on 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

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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 (Natke 1989; Shin and Hjelmstad 1994). 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 (Imai *et al.* 1989). 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. The errors associated with numerical calculation to compute unmeasured parts of state vectors would not be small to be neglected. In spite of the limited applications of the time domain system identification methods, however, 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.

In the present paper, we introduce a damage detection algorithm using a time-domain system identification method and summarize the results obtained from a numerical simulation with simulated noisy accelerations fully measured at all the degrees of freedom. Displacements and velocities were computed by numerical integration. The problem using incompletely measured acceleration is receiving careful study.

System identification with transient dynamic response

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

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

Each structural matrix is defined with the parameter vector $\boldsymbol{x}=\{\boldsymbol{x}_M\,\boldsymbol{x}_C\,\boldsymbol{x}_K\}^{\mathrm{T}}$, where $\boldsymbol{x}_M$, $\boldsymbol{x}_C$, $\boldsymbol{x}_K$ 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.*(1995). 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 sparsely 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. In the present paper, we simply assume that accelerations are measured at all the degrees of freedom. The research is in progress to develop an algorithm that can accommodate sparsely measured acceleration.

If we obtain all the state vectors by measuring or computing them, we can solve the following nonlinear constrained optimization problem of Eq.(2) to estimate optimal parameter values.

$$\begin{aligned} &\mathit{Minimize}\ \ J(x) = \frac{1}{2}\sum_{k=1}^{ntp} \alpha_k \left\| M(x)\,a_k + C(x)\,v_k + K(x)\,d_k - f_k \right\|^2 \\ &\mathit{subject\ to}\ \ \underline{x} \le x \le \bar{x} \qquad (2) \end{aligned}$$

where $\underline{x}, \bar{x}$ are the lower and upper bounds for the unknown parameters, *ntp* is the number of time points, a_k, v_k, d_k are measured acceleration and computed velocity and displacement vector at the *k*th time point, respectively.

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 parameter groups are available in the literature (Natke and Cempel 1991; Shin and Hjelmstad 1994). 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 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 population of estimated values for an element parameter from selected 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,

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

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 with respect to test conditions. 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 at 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 additionally because the second damage index *bias_sd*'s were larger than the others and were close to the value of 1.0.

From 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 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 at 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 from the proposed algorithm.

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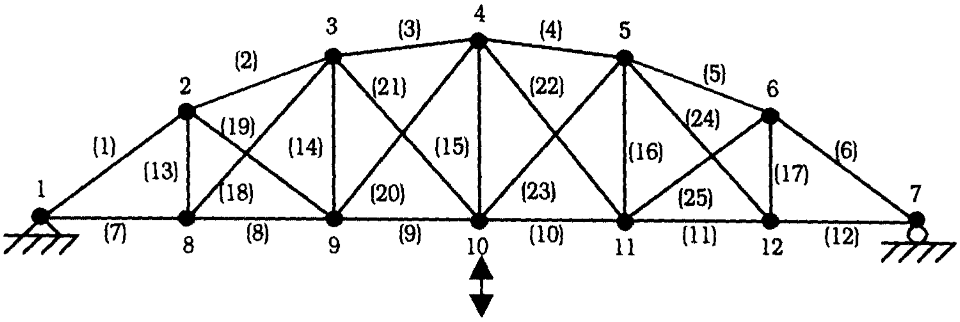

Fig. 1 : Geometry and topology of a Bowstring truss

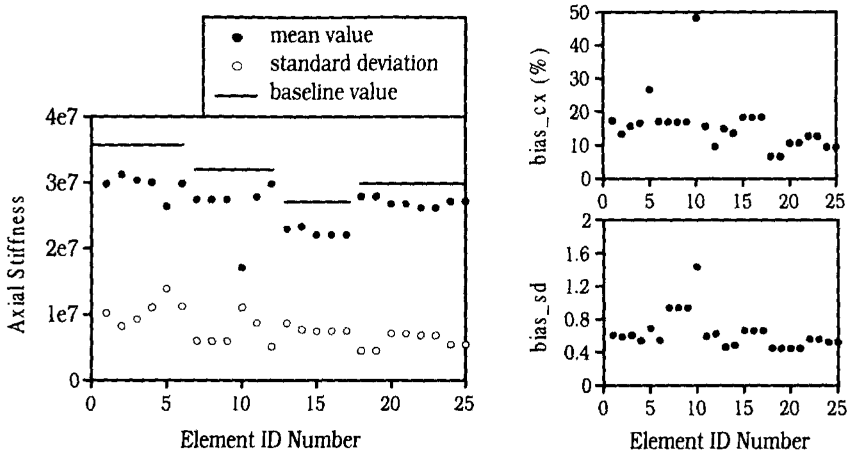

Fig. 2 : Estimated parameters and the computed damage indices

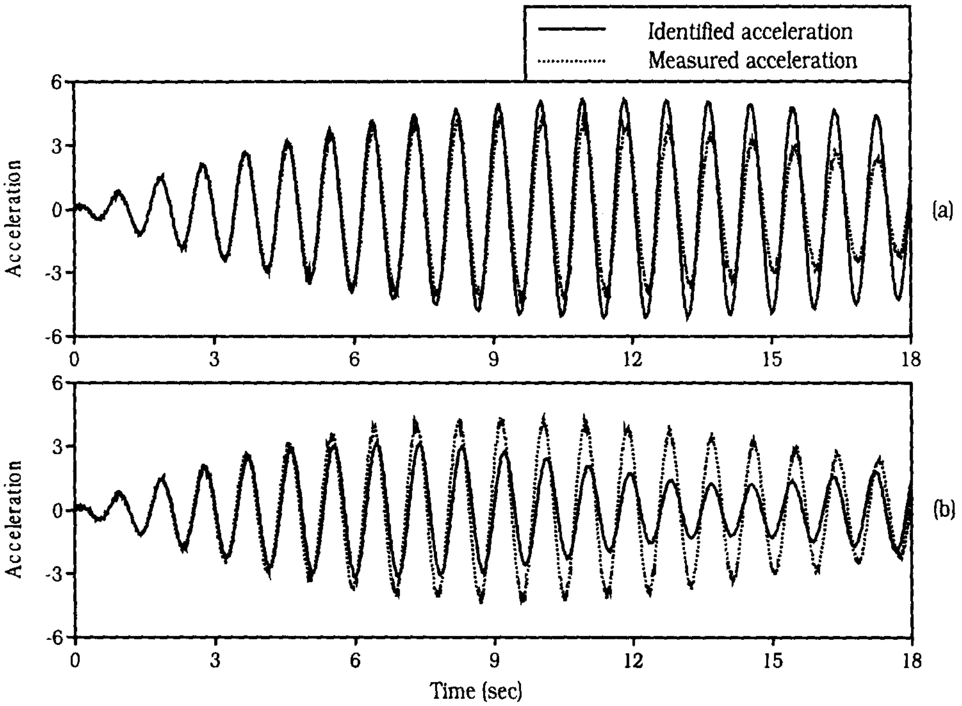

Fig. 3 : Comparison of measured and identified accelerations at a resonant load frequency in the vertical direction at node 9: (a) reduced sectional area of member (10); (b) reduced sectional area of member (7)-(10)

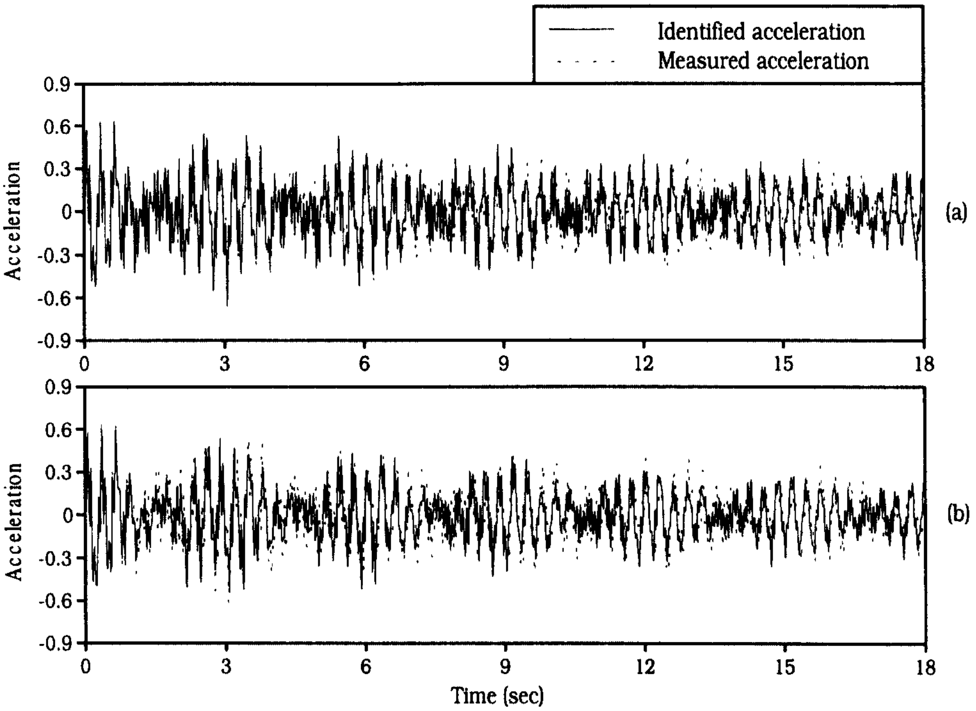

Fig. 4 : Comparison of measured and identified accelerations at a non-resonant load frequency in the vertical direction at node 9: (a) reduced sectional area of member (10); (b) reduced sectional area of member (7)-(10)