Use of Statistical Information for Damage Assessment of Civil Engineering Structures

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FRACTURE & DYNAMICS
PAPER NO. 90

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ABSTRACT

This paper considers the problem of damage assessment of civil engineering structures using statistical information. The aim of the paper is to review how researchers recently have tried to solve the problem. It is pointed out that the problem consists of not only how to use the statistical information for the damage assessment but also how the information can be used for updating the reliability of the structure. It is concluded in the paper that use of statistical information perhaps is the key to damage assessment.

1. INTRODUCTION

Civil engineering structures continuously accumulate damage during their service life due to environmental forces such as waves, winds, current and seismic actions. A damage may alter the stiffness and change the modal properties of the structural system, such as natural frequencies, damping ratios and mode shapes. Changes in natural eigen-frequencies are no doubt the most frequently used damage indicators. These are sensitive to both local and global damages. A local damage will cause changes in the derivatives of the mode shapes at the position of the damage. This means that a mode shape having many coordinates can locate the approximate position of a damage. The introduction of damage in a structure will usually cause changes in the damping capacity of the structure. Damping ratios can therefore be sensitive to the introduction of even small cracks in a structure. Therefore, much research has been done with respect to structural diagnosis (health monitoring) by measuring and analysing vibrational signals of civil engineering structures.The main impetus for doing vibrational based inspection (VBI) is caused by a wish to establish an alternative damage assessment method to the more traditional ones. Many research projects have concluded that it is possible to detect damages in civil engineering structures by VBI, and some techniques to locate damages in civil engineering structures have also been proposed. Many different methods for damage assessment have been developed during the last decades, see e.g. Doebling et al. [1] and Rytter [2]. However, the words *damage assessment* have been used at random. For clarity Rytter [2] proposed the following classifications :

Level 1 The method gives a qualitative indication that damage might be present in the structure (DETECTION).

Level 2 The method gives estimates for the localiza tion of the damage too (LOCALIZATION).

Level 3 The method gives information about the amount of the damage (ASSESSMENT).

Level 4 The method gives information about the actual safety of the structure given a certain damage state (CONSEQUENCE).

Real VBI tests imply that the investigator has to distinguish between changes in modal properties, due to effects produced by damages, and those brought about as a result of changes in ambient conditions, such as temperature, wind conditions, relative humidity and pore pressure. Further, there will also be changes in modal properties due to random variations in the measurements. All these parameters which can imply a change in the modal parameters indicate that it can be very difficult in practice to perform a VBI. Therefore, the current sentiment among the researchers towards VBI encompasses the spectrum from "damage assessment using VBI is impossible" to "damage assessment using VBI is perfectly suited for long-term infrastructure monitoring and is the key technology for the smart structures of the future", Doebling et al. [3]. Recently, several researchers have stated that the last statement seems to be correct if the statistical information inherent in the modal parameters is used in VBI problems. The aim of the present paper is to review how researchers recently have tried to solve the VBI problem using statistical information. In section 2, proposed techniques at levels 1,2 and 3 are considered. In section 3, it is pointed out that the problem consists of not only how to use the statistical information for the damage assessment problem but also how the information can be used for updating the reliability of the structure. Finally, in section 4 conclusions are given.

2. USE OF STATISTICAL INFORMATION AT LEVELS 1, 2 AND 3.

All modal parameters are in principle applicable as damage indicators.This means that they can be used at least for detection of damage. However, the key to a successful damage detection is the use of unbiased and low-variance modal parameter estimates as damage indicators. If the estimates are biased they might cause a false alarm, i.e. indicate a damage that does not exist. If the estimation inaccuracies are too dominant, it might be impossible to detect any significant changes, i.e., the existence of a damage might be hidden. Thus, if the uncertainties of the estimated modal parameters can be estimated it will be possible to assess whether changes of modal parameters are caused by e.g. a damage or simply by estimation uncertainties. Further, if the changes of the modal parameters are not caused by estimation inaccuracies, the estimated uncertainties can be used to establish a probabilistic confidence in the existence of a damage. These confidence bounds have been used in several ways for damage assessment as explained in the following sections.

2.1 Damage Detection using Confidence Bounds

The most fundamental use of the confidence bounds is by assuming that a damage has been detected if the confidence intervals of all the natural eigen-frequency estimates of a mode at some damage state are non-overlapping with the confidence interval of the natural eigen-frequency of the same mode in the virgin state. This approach has been applied by e.g. Andersen et al. [4], Doebling et al. [5] and Doebling et al. [6].

In Andersen et al. [4] statistically based damage detection is applied to ambient excited civil engineering structures. The applied system identification method is a non-linear Prediction Error Method (PEM). Estimation of ARMAV models using this technique is known to provide asymptotically unbiased and efficient modal parameter estimates solely on the basis of output measurements of a system. In other words, the uncertainties of the estimated modal parameters will attain the Cramer-Rao lower bound of variance. By assuming that the lower bound is reached, it is possible to estimate the standard deviations associated with the estimated modal parameters. The use of this additional information as a basis for a simple statistically based damage detection, which was illustrated on measurements of a lattice steel mast that has been damaged. The four chord K-frame test mast with a 0.9 × 0.9 m cross-section is bolted with twelve bolts, three for each chord, to a concrete foundation block. The mast is constructed with welded joints. In one of the lower diagonals a damage has been simulated by introducing a crack and increasing its depth. The depth of the crack has been increased 4 times. Before the damage is introduced the state of the structure is referred to as the virgin state. After the introduction of the damage the four different states of the structure are referred to as damage states.

It was assumed that a damage has been detected if the confidence intervals of all the natural eigenfrequency estimates of a mode at some damage state are non-overlapping with the 95% confidence interval of the natural eigenfrequency of the same mode in the virgin state. This detection approach can be utilized by plotting the estimated selected natural eigenfrequencies and their estimated 95% confidence intervals of the damage states together with the averaged natural eigen-frequency estimates and the estimated confidence intervals of the virgin state. In figure 1, this is done for the fifth natural eigenfrequency estimates.

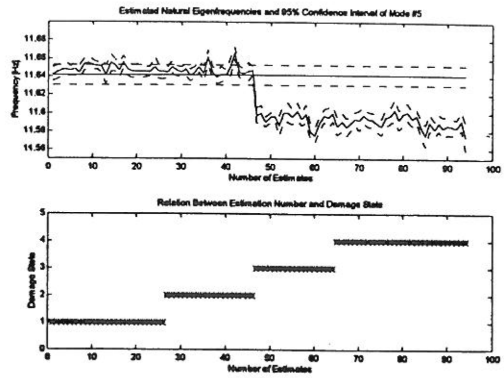

Figure 1: Estimated natural eigenfrequencies of the fifth mode and their estimated 95% confidence intervals. Andersen et al. [4].

In figure 1, it is seen that the confidence intervals become non-overlapping at damage state three with the virgin state confidence interval. So due to the above definition of a significant damage, it can be concluded that the actual damage has been detected when it entered the third damage state.The detected changes of the natural eigen-frequencies are so significant that they are probably caused by a structural change. However, the modal parameters can also exhibit small changes due to fluctuations in the ambient environment. When e.g. the ambient temperature changes, thermal expansion effects and changes of the stiffness will occur. The effects of fluctuating ambient temperatures on this particular mast have been investigated in Kirkegaard et al. [7]. In that paper it was found that there is a correlation between change in natural eigen-frequencies and temperature. Such correlation has also been reported by other researchers, such as Askegaard et al. [8], Bencat [9], Farrar et al. [10], Roberts et al. [11] and Woon et al. [12]. A technique based on Kalman filtering for removal of the influence of temperature on eigen-frequencies has been proposed in Andersen et al. [13]. In that paper, it has been illustrated, how to remove the influence of a fluctuating ambient temperature from estimates of natural eigen-frequencies of a damaged structure. In other words, how to put the estimates of the natural eigen-frequencies to a state, described by a reference ambient temperature. A regression model, for elimination of the influence of the ambient temperature on the estimated natural eigen-frequencies, is formulated. This regression model is tested using simulations of a steel beam, having a growing crack and being exposed to a fluctuating ambient temperature.

Doebling et al. [5] and Doebling et al. [6] demonstrated how statistical parameters such as the 95 per cent confidence bounds can be defined for measured modal parametes using frequency response functions for the estimation. Statistical uncertainty bounds on the measured frequency response function magnitude and phase were computed from the measured coherence functions, assuming the errors were distributed in a Gaussian manner. These bounds were used to estimate statistical uncertainty bounds on the modal parameters, both natural eigen-frequencies and mode shapes, respectively. The proposed statistical procedure is in Doebling et al. [5] applied to modal data from an interstate highway bridge that was incremental damaged prior to its demolition. in Doebling et al. [6] the procedure was applied to the Alamosa Canyon Bridge where modal measurements from the bridge were used to determine the statistical uncertainty bounds on the modal frequencies and mode shapes. Changes in modal frequencies and mode shapes due to damages were simulated using a correlated finite element model. In both papers it was found that there is, in general, more statistical uncertainty associated with mode shape curvature and mode shape amplitudes than that associated with the resonant frequencies. Further, it was found in both papers that lower levels of damage did produce statistical significant changes in the modal properties.

2.2 Damage Detection using a Statistical Measure.

A first attempt to make VBI using statistical information such as the estimated modal parameter uncertainties seems to be done in Coppolino et al. [14].They presented a statistical approach where a threshold level of $2\sqrt{2}\sigma$ using a 0.05 level of significance is introduced. σ is the standard deviation of all uncorrelated error contributors, i.e. of the estimated natural eigen-frequencies, assuming that all errors are normally distributed and that the standard deviation of the natural eigen-frequencies is unchanged from between each measurement. A damage was assumed detected if the change in eigen-frequencies was larger than the threshold level.The approach was used for damage detection in an offshore structure located in the Gulf of Mexico. The platform is an eight-leg diagonally braced jacket construction which standed in a 100 m water depth.

Ruotolo et al. [15] extended the method proposed by Coppolino et al. [14] with a statistical test procedure based on the t-distribution. The procedure assumes that n_1 measurements of the first n_f eigen-frequencies at virgin state and n_2 eigen-frequencies periodically, which are stochastically independent observations. Based on a simulated example with a multiple cracked beam model it was found that a structure can be assumed damaged with a higher level of significance when the same structure is considered undamaged using the approach proposed in Coppolino et al. [14].

Abdelghani et al. [16] has also proposed a damage detection scheme based on a statistical test procedure.They introduced a statistics which measures the likelihood of the most likely change in the structure. It takes the combination of all the individual changes of the eigen-frequencies and associated mode shapes into account, and automatically compares them to their confidence domain to evaluate whether the changes might be due to uncertainties or more likely to changes in the structure. The scheme was applied for damage detection in a suspended steel subframe to which masses could be added at different locations to simulate structural changes.

Brincker et al. [17] used a statistical measure to quantify the probability of negative change in the first two eigen-frequencies from different measurements. A negative change in these eigen-frequencies was assumed to indicate that the structure had suffered structural damage. The eigen-frequencies were assumed to be independent Gaussian distributed variables. The statistical measure was used to investigate the structural integrity of a multi-pile offshore platform.

Fritzen et al. [18] described a vibrating system via FEM and reformulated it as a state-space model reduced by a modal transformation. Kalman filters were used to compare the time history response of the system to FEM predictions for the undamaged case and various damaged cases. The output was a distribution of probabilities indicating which of the test cases most likely corresponds to the actual measurements. Generally, the filters were applied once to locate a damaged element or section and then a second time to further refine the location and quantify the damage. Because the work was all done in the time domain, the technique applies directly to nonlinear damage.

2.3 Damage Localization using a Statistical Measure.

One of the most well-known damage localization procedures, see Cawley et al. [20] relies on a comparison of the predicted and the measured changes in eigen-frequencies of the structure for all the damage scenarios where the closest damage case is chosen. In principle this can be interpreted as a statistical method for damage localization. However, the drawback with this method is that even if the natural frequencies change slightly, due to temperature effects or measurement noise, the method would still locate damage, although none had occurred. In order to deal with that problem the method has been future developed with respect to statistical damage localization in Friswell et al. [21]. They incorporated random errors in a sensible way, by supposing that the logarithms of the observed frequency changes are independent random variables with unequal variances. This implies that the damage locations are found by using generalized least squares theory. The quality of this fitted line is given by a coefficient of determination which can be interpreted as a statistical measure to locate damage in structures. The results do strongly suggest that the proposed method shows promise in locating damage within a structure.

Stubbs et al. [22] proposed a damage localization algorithm relying on mode shape information which could be used for linear time invariant as well as nonlinear time invariant structures. The method is based upon that the fraction of modal energy in a given member is the same for both damaged and undamaged structures subjected to the same excitation. The localization scheme is essentially a detector which accepts a value of a defined damage index as input and provides as output a decision regarding the likelihood that the structure is damaged at that location. It is hypothesized first that the structure is not damaged at a given location and that the values of the damage indices represent a sample population of a random variable. Next, for a given damage index the probability of damage is estimated. The proposed method was demonstrated with a simulation example where the localization accuracy was investigated as a function of the degree of non-linearity present.

3. USE OF STATISTICAL INFORMATION AT LEVEL 4. (SAFETY ASSESSMENT)

Damage assessment at level 4 seems to be an uninvestigated item in spite of it is very important to be able to justify whether or not a structure is capable of fulfilling its structural requirements. For such reconsiderations of the structural safety it is necessary to obtain information about the actual state of the structure, i.e. one has to know the location and size of the damages. However, the problem to reconsider the structural safety is associated with considerable uncertainty, due to the uncertainty of the damage detection steps and the uncertainty of structural analysis of the structure under consideration. Therefore, it is of interest to consider a philosophy of applied probability and statistics. This philosophy can be formulated as the Bayesian statistical decision theory, which provides a mathematical framework for making consistent engineering decisions. In the following papers which have considered damage assessment at level 4 are presented.

A simple way to perform reconsideration of the structural safety is by relating the change in modal parameters to the limit state of the structure. The maximum softening concept is based on the variation of the natural eigen-frequencies during a seismic event. A strong correlation between the damage state of a reinforced concrete structure that has experienced an earthquake and the global maximum softening has been documented, DiPasquale et al. [23]. They investigated a series of buildings damaged during earthquakes and found a very small variation coefficient for the maximum softening damage index, see figure 2. It is seen that the maximum softening approach gives a very easy way to reconsider the structural safety of reinforced concrete structure which has experienced an earthquake. However, the drawback for this damage index is that only a global index displaying the average stiffness reduction of the entire structure giving no information about the damage distribution in the structure.

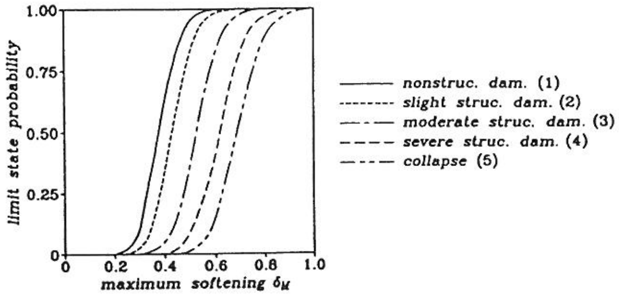

Figure 2: Distribution function of observed limit state values of one-dimensional maximum softening reported by DiPasquale et al. [23].

Brancaleoni et al. [24] proposed a method to reconsideration of the safety of a bridge by relating the residual stiffness of the lateral beam to the crack height. The residual stiffness was obtained from estimated natural frequencies which were theoretical related to the stiffness of the structure. Based on the estimated crack height a reduced inertia moment and the residual prestressing force were found. These two parameters were used for estimation of the reduced load carrying capacity.

Recently, Asmussen et al. [25] proposed how optimal planning of vibration based inspection can be performed. During the last decades a lot of research has been performed to make optimal inspection programmes for civil engineering structures. Optimal planning of inspection and maintenance strategies for structures have become a subject of increasing interest especially for offshore structures for which large costs are associated with structural failure, inspections and repairs. During the last decade a methodology has been formulated to perform optimal inspection and repair strategies for structural components. The methodology makes it possible to determine an inspection and repair plan which will minimize the total expected costs of a component throughout its anticipated lifetime. These inspection plans are normally performed assuming visual inspection. However, the planning can also be done assuming VBI. In order to make such plans information about the quality of the inspection method has to be known. This information is given by a so-called Probability of Detection (POD) curve which states the probability for detection of a given crack with a given size and loacation. In Asmussen et al. [25] POD-curves were calculated by simulations for a steel chimney. Detection of a damage was performed using a statistical test procedure. Figure 3 shows a POD-curve obtained for the steel chimney.

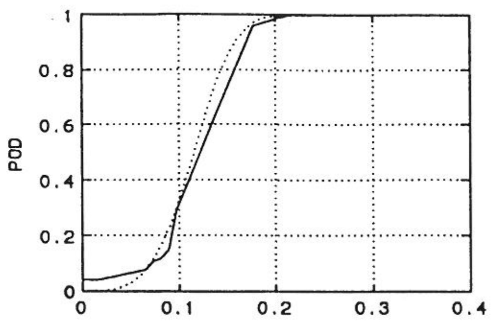

Figure 3. POD-curve for steel chimney. [-----] from simulation. [- - - -] estimated Weibull distribution funcion. Asmussen et al. [25].

Figure 3 shows that a crack has to be larger than 0.1 m before it can be detected with a high level of significance using VBI. The POD-curve was used for calculation of a inspection plan for VBI of a steel chimney. These calculation also included estimation of the safety of the chimney due to different damage states.

4. CONCLUSIONS

In this paper a review is given of how researchers recently have tried to solve the problem of damage assessment of civil engineering structures using statistical information. It is pointed out that the problem consists of not only how to use the statical information for the damage assessment but also how the information can be used for updating the reliability of the structure. It is also found that only a few researchers have considered the problem but recently it seems as the interest for the problem is increasing. Especially, because it seems as use of statistical information perhaps can be the key to damage assessment of civil engineering structures in practice.

5. ACKNOWLEDGEMENT

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