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Accuracy enhancement of fatigue damage counting using design sensitivity analysis

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ABSTRACT

Recent studies have suggested fatigue damage counting of a linear elastic system using only the output data; design sensitivity analysis based on the transmissibility function was studied in order to identify the most sensitive response location under intact conditions. The design sensitivity index was derived to be proportional to the response energy at the measured point through reformulation of the previous equation for the sensitivity index. The accuracy of the damage counting method can be enhanced with design sensitivity analysis by selecting the location with the maximum response energy; the method is optimally robust against unexpected noise in the output data. Simulation and testing of a notched simple specimen under uniaxial excitation were used to verify that sensitivity analysis enhances the accuracy of the predicted damage counting.

1. Introduction

Predicting fatigue resistance is a primary issue for guaranteeing the required life cycle of operating systems in an excitation environment because the conventional fatigue method cannot cover the full range of dynamic behavior by the system. Accumulated fatigue damage is accelerated at hotspots of a dynamic system when the natural frequencies of the system are coupled with the peak spectrum of external excitation. The accumulated fatigue damage or valid life cycle of the system can be predicted accurately only if the system dynamics are well identified and the measured response data are reliable. In a vibration fatigue problem, the acceleration data are important and reflect the characteristics of the dynamic system as well as the spectral condition of the external vibration.

Acceleration data are a valuable record of the physical properties of a dynamic system or noise and vibration problem since the data are most visible in a high-frequency domain. Excitation is generally defined by the acceleration, and the most interesting information about the flexible structure is focused on the nature of response with respect to the acceleration input. In vibration fatigue problems, acceleration data are not sufficient for determining the accumulated fatigue damage; additional information (i.e., stress or strain stemming from excitation) should be determined separately as compensation. The stress or strain is frequently measured with a strain gauge; this method directly measures the strain data from target locations. The only problem with using a strain gauge is that the measured data are easily susceptible to structural features,

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such as notches or curvatures of the surface, as well as other factors such as the mechanical characteristics of the material and environmental temperature [3–5]. A strain gauge is also hard to replace and may be impossible to attach to a structure under certain circumstances. To tackle the problem of strain gauges, Kim et al. proposed using the energy isocline function for a linear elastic system (LES) to predict the accumulated fatigue damage from only the acceleration data; they proved their theory through uniaxial vibration testing [1]. The energy isocline function consists of both the fatigue material properties of the LES and the spectral relationship between the response acceleration and stress at a hotspot. Previous studies on fatigue problems using acceleration data were for earthquake events [6,7] or monitoring structural damage while assuming that the damaged system modifies the structural stiffness and damping ratio from the initial state [8–12].

The response acceleration can be used for sensitivity design analysis of a linear system to find the best design modification with respect to the assigned design goal and scope. The response acceleration exhibits the complicated behavior of the system; it contains the system dynamics and external excitation, so the design sensitivity characteristics for a given excitation can be estimated using only the response data. Kim et al. presented a novel design sensitivity analysis that quantifies the nodal sensitivity to different design parameters – mass, damping, and stiffness – using the transmissibility function without any a priori knowledge about the system [2,13]. Several studies have provided data on design sensitivity analysis; accurate system identification is required despite the availability of various methodologies such as finite-difference, analytical, and semi-analytical methods [14–18]. The transmissibility function (or output-only data) is widely applied to dynamic systems because it has a considerable advantage of preserving the system dynamics under intact conditions. Some studies applied the function to operational modal analysis (OMA) [19–22] or transfer path analysis (TPA) [23]. The transmissibility function has also been extended to the detection of structural failure by suggesting damage sensitivity functions [24] or a transmissibility damage indicator [25].

This paper presents a strategy to enhance the accuracy of fatigue damage counting with acceleration using design sensitivity analysis by selecting the measurement acceleration data at an optimal location. The design sensitivity index proved to be proportional to the response energy through reformulation of previous design sensitivity equations. The response data for a high sensitivity index value have a high level of response energy; the response information is more robust than other information on external noise disturbances. Thus, the counted fatigue damage from acceleration data at the highest sensitivity index value is more reliable than that from other locations. In order to demonstrate the efficiency of the proposed method, a notched simple beam was used as an experimental specimen and finite element model. The predicted fatigue damage was calculated based on the response acceleration from uniaxial vibration; testing was carried out both experimentally and in a CAE simulation. The expected fatigue damage was compared to the calculated fatigue damage from the stress data. The efficiency of the proposed method was examined based on the results. The mass loading effect of sensors is also addressed in the simulation chapter by simulating the notched simple specimen with a concentrated mass. Since the measurement point having the highest value of sensitivity index is equivalent to the most sensitive location to modify the overall system dynamics by small design change, i.e., mass, stiffness, damping, at an interesting point, even a small mass loading of accelerometer can spoil the accuracy of the predicted fatigue damage. The mass loading effect of sensors is investigated through the simulation result of eigenvalue that is derived by the modal analysis of the six cases of notched simple specimen with a concentrated mass. Here, the fatigue damage in this paper was based on an S–N curve such that the accumulated fatigue damage of the notched simple specimen was within the elastic region before a crack initiation. So, the dynamic characteristics of the notched simple specimen were assumed to be preserved safely during the uniaxial excitation.

2. Fatigue damage counting using only the output data

2.1. Fatigue damage counting using only the output data

The method of counting the fatigue damage of an LES is based on using the single spectrum signal in Eq. (1). The response acceleration at a certain position is assumed to have a zero mean value.

$$r(t) = \bar{r}\ \cos(\omega_1 t + \phi) \tag{1}$$

where $\bar{r}$ and ω_1 are the amplitude and fundamental frequency of the measurement response, respectively, and ϕ is the phase delay. On the other hand, if the relationship between the response stress at a hotspot and the acceleration response at Eq. (1) is determined previously as H_m, the spectral response of stress, $\sigma(\omega_1)$, can be calculated as follows [1]:

$$\sigma(\omega_1) = ||H_m(\omega_1)||\bar{r}(\omega_1) \tag{2}$$

where $||H_m||$ is the magnitude of frequency response function (FRF) H_m. If the fatigue damage accumulates owing to the single spectral input in Eq. (1), the accumulated fatigue damage during period T_1 can be calculated by Miner's rule, as shown in Eq. (3) [1,26]:

$$D(T_1) = \frac{\omega_1 T_1}{\pi S_0^{-1/b} / \sigma(\omega_1)^{-1/b}} \tag{3}$$