Modal moment index for damage detection in beam structures

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(Received September 3, 1999)

Summary. Health monitoring and damage detection in structures such as airframes are crucial to their safety and performance. Damage-induced changes in natural frequencies, damping ratios and mode shapes can be detected using experimental modal analysis (EMA), which has recently enjoyed intense research for application in structural health monitoring. A main theme of the current research has been to formulate a parameter, calculated using the measured changes in eigenparameters, which exhibits a significant "jump" at the damage location and whose value is a direct measure of the severity of the damage. A damage-sensitive parameter thus serves to localize the damage and to assess its severity, and it should likewise minimize the likelihood of false indications or of missing damage. Here, using finite element analysis of the damaged cantilevered beam, we study several existing parameters and introduce a new parameter called the Modal Moment Index (MMI). MMI is shown to jump sharply at the damage site and to have a direct relationship to the damage level.

Notation

\( e \) \( e \)-th element
\( i \) \( i \)-th eigenvector
\( * \) implies damage

1 Introduction

For the sake of safety, reliability and operational life, it is urgent to monitor the health of structural systems. Techniques for nondestructive damage detection in aerospace, civil and mechanical engineering structures are essential. Structures are prone to damage during their service lives, caused by factors such as corrosion, fatigue, impact and overloads. Structural damage causes deviations of geometric or material properties from nominal or baseline values. Experimental modal analysis has become an increasingly accepted method for determining the overall health of the structure. It uses differences of measured modal properties from baseline or nominal values to identify and assess the location and severity of damage.

Experimental modal analysis consists of measuring parameters (i.e., natural frequencies, damping factors, and mode shapes) of a structural member from its response to a known vibration input. Testing is typically conducted using a laser vibrometer and a shaker. The shaker generates white noise excitation while the laser vibrometer scans the structure. The laser vibrometer uses an interference principle to obtain a high resolution profile of the verti-
cal velocity of the points on the upper surface of the member. The data are submitted to signal processing based on the Fast Fourier Transform to estimate the eigenparameters. If the structure being tested is damaged, and if the eigenproperties of the undamaged baseline are known the eigenproperty differences can ideally be used in real time to calculate parameters based on the differences. Our goal is to formulate a parameter which exhibits a sharp jump at the location of damage, and whose magnitude is sensitive to the severity of the damage. It is expected that use of such a parameter will also minimize the likelihood of false indications or of not detecting damage sites. Availability of such a parameter would enable the test operator to immediately take additional measurements at the damage site to obtain greater resolution.

2 Background

Petro et al. [1] tested a free-free cantilever beam using Modal Strain Energy Techniques and reported very good results in damage identification. The member was tested without damage, and then tested after damage was introduced. An “intuitive” damage parameter called the Strain Energy Damage Index (SEDI) was used; it measured relative modal strain energy changes due to damage, based on one-dimensional static beam mechanics. The technique required numerically differentiating modal test data twice to obtain the curvature of the mode shape and then numerically integrating the square of the mode shape to estimate the strain energy variation along the beam. In spite of the potential error of the numerical methods and of the difficulties posed by experimental noise, this effort was reported to furnish very good results in locating the damage in that the SEDI parameter exhibited a jump where damage has been introduced.

Meza et al. [2] implemented modal strain energy techniques and a scanning laser vibrometer to test a DC-9 aircraft forward fuselage for different artificially induced damage scenarios. The same strain energy technique discussed in the preceding paragraph was employed for plate elements using a finite element model. The tests had varying degrees of success. In some modes, the correct damaged area was indicated and in other modes an incorrect area was indicated. These investigators then averaged the strain energy differences from all the different modes and claimed success in isolating the damage. Carrasco et al. [3] used modal strain energy techniques to identify damage in a relatively complicated truss structure with several types of damage scenarios. This effort weighted the strain energy differences in elements of the finite element model in proportion to the strain energy distribution in the undamaged case. Noise effects were compensated by assigning large weights to the sensitive elements and small weights to the insensitive elements. Varying levels of success were reported.

In the subsequent sections the SEDI parameter and a very similar parameter are studied using a finite element code due to Reddy [4]. For the sake of evaluation, damage is assumed to consist of a normalized difference between the damaged and undamaged elastic moduli. While the aforementioned parameters exhibit a jump in the vicinity of the damage, their values are found to be insensitive to the actual level of damage. We believe this insensitivity poses a risk of false indications and of failing to detect damage. Instead, in this paper a new damage sensitive parameter called the Modal Moment Index is introduced. It likewise uses the difference in the modal strain energies of the corresponding undamaged and damaged elements, but assumes that the “modal moment” is unaffected by damage. The parameter jumps sharply at the damage site. Furthermore, it is virtually identical to the normalized elastic modulus decrease.