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Prediction of fatigue life using modal analysis for grey and ductile cast iron

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Abstract

The aim of this work is to investigate the capability of experimental modal analysis, as a nondestructive tool, to characterize and quantify fatigue behavior of materials. This is achieved by studying the response of modal parameters (damping ratio, natural frequency, and FRF magnitude) to variations in material microstructure, as a main factor affecting fatigue life. This helps in correlating modal parameters to fatigue behavior. Cast iron family represented by grey cast iron, ductile cast iron and austempered ductile iron (ADI) is used in experiments as a case presenting considerable variations in microstructure. Modal testing was performed on specimens made of the selected materials in order to extract the corresponding modal parameters. Rotating bending fatigue test was performed on standard fatigue specimens to correlate the modal parameters to the fatigue behavior. This enables the evaluation of the ability of modal testing to predict the fatigue life of mechanical components.

Keywords: Austempered ductile iron; Modal testing; Fatigue life

1. Introduction

Recent technical demands for improving the performance of engineering components have brought up the need of proper estimation of components/system life to avoid sudden or unexpected failure of equipment. The ability of any system to perform its required function without failure remains a challenging concern for design engineers. As considered as the main cause of failure in industrial components, fatigue remains the main source of unexpected failure in mechanical components as the majority of structures are subjected to cyclic, alternating stress. Consequently, fatigue life can be satisfactorily considered as a measure for the reliability of mechanical components. Many research papers have been dealing with fatigue life predictions of different components such as aircraft structural components, riveted lap joints, and welded joints using different methods ranging from finite element analysis to fracture mechanics theories that are mainly based on destructive testing. However these methods are considered approximate as they do not include all the factors affecting fatigue life because they are not based on the actual components and systems.

The demand for a nondestructive test that predicts the fatigue life of individual components is growing by time as it is expected to overcome the problem of variability of results in destructive techniques. This leads to the introduction of experimental modal analysis, as a non destructive tool, to help in determining the reliability of machine components as it evaluates the structure integrity as it is based on the theory of resonance testing [1]. A significant amount of work has been done regarding the use of modal parameters (i.e. natural frequency, modal damping, and mode shapes) for damage detection and identification.

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The basic idea is that the modal parameters are, by definition, functions of the physical properties of components (i.e. mass, stiffness or modulus of elasticity) and hence of mechanical properties. This concept was used mainly in the application of modal testing as an acceptance test for castings [2,3]. Doebling *et al*. [4] presented an extensive review of the technical literature concerning the detection, location and characterization of structural damage by examining changes in measured structural vibration response and/or modal parameters. The ability of detecting the presence of cracks in beams and determine its location and size based on changes in natural frequencies and frequency response function (FRF) amplitudes was studied by Owalbi *et al*. [5]. They observed that the amplitude of the FRF of the bending modes increase as the crack size grow, this is accompanied by a decrease in natural frequencies. The use of modal analysis for damage detection in aluminum cylinders was studied by Davis [6]. He declared that the evaluation of natural frequencies and the curvature of the FRF (mode shapes) can be used to determine the presence, location, and severity of the imparted damage. The ability of modal testing to estimate the fatigue life of standard fatigue specimens made of brass was investigated by Tobgy *et al*. [7]. Random notches were introduced in brass specimens to achieve some variability in the fatigue life of specimens. A correlation between fatigue life and corresponding modal parameters of each specimen was achieved. The feasibility of modal analysis as a nondestructive technique in detecting damage for health monitoring of composite materials was investigated by Kessler *et al*. [8]. They performed experimental modal testing as well as a finite element model on graphite/epoxy panels containing representative damage modes. Strong correspondence between the extent of damage (or local stiffness loss) and reduction in natural frequency was found. Bedewi *et al*. [9] developed an experimental method to predict the residual fatigue life of composite structures. Changes of modal parameters, i.e. natural frequencies and damping ratios, were investigated and correlated to the fatigue failure life during the fatigue process for selected gaphite/epoxy composite specimens to be used as nondestructive indicator of fatigue life. The decrease in natural frequency and the increase of damping ratio as a function of number of cycles to failure were monitored to predict the fatigue failure life.

The effect of fatigue damage on the dynamic natural frequency over the entire fatigue life process for tensile-shear spot-welded joints was studied by Shang *et al*. [10]. The study aimed to obtain a physically based damage parameter for spot-welded joints made from automotive annealed steel. A remarkable decrease of the natural frequency of the tested spot-welded was noticed after the half of the fatigue life with more dramatic decrease at the end of the fatigue life. Liu *et al*. [11] studied the effect of circumferential cracks on coupled-response of a circular hollow section beam both analytically and experimentally. They observed that the natural frequencies shift to lower value with the increase of crack severity (depth). Similar trend was obtained by Kim [12] as he studied application of vibration-based techniques in on-line damage identification in composite materials using frequency response function (FRF). The peaks of the measured responses (i.e. the natural frequencies) shift to lower frequency as the debonding extent increases and with the increase of the number of fatigue loading cycles.

The main concern of this work is to study the capability of modal testing, as a non destructive test, to characterize and quantify the fatigue behavior of mechanical components. This can be achieved by studying the response of modal parameters to microstructure characteristics as a main factor affecting the fatigue life of components. To elaborate the effect of change in microstructure on the response of modal analysis, cast iron family presented by grey cast iron and ductile cast iron is used in experiments as presenting two types of cast iron with different microstructure. Besides, the change in phase amount occurred in austempered ductile iron (ADI) treated at different conditions is also considered; a condition presenting microstructure variation that leads to variation in mechanical properties to be dynamically studied [13].

2. Experimental work

In this paper, [14] two sets of experiments were carried out to correlate modal parameters to fatigue. The experiments were performed on specimens made of ductile and grey cast iron with the following composition as shown in Tables 1a and 1b.

Table 1a
Chemical composition of ductile cast iron

C%	Si%	Mg%	P%	S%	Mn%	Mo%	Ni%	Cu%
3.424	2.462	0.0254	0.0342	0.0032	0.327	0.0017	0.0026	0.0072

Table 1b
Chemical composition of grey cast iron

C%	Si%	Mg%	P%	S%	Mn%	Cu%	Ni%	Fe%
3.893	1.605	0.0004	0.2165	0.1232	0.4169	0.0804	0.0396	93.6