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Forward models for extending the mechanical damage evaluation capability of resonant ultrasound spectroscopy

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ABSTRACT

Finite element (FE) modeling has been coupled with resonant ultrasound spectroscopy (RUS) for nondestructive evaluation (NDE) of high temperature damage induced by mechanical loading. Forward FE models predict mode-specific changes in resonance frequencies (Δf_R), inform RUS measurements of mode-type, and identify diagnostic resonance modes sensitive to individual or multiple concurrent damage mechanisms. The magnitude of modeled Δf_R correlate very well with the magnitude of measured Δf_R from RUS, affording quantitative assessments of damage. This approach was employed to study creep damage in a polycrystalline Ni-based superalloy (Mar-M247) at 950 °C. After iterative applications of creep strains up to 8.8%, RUS measurements recorded Δf_R that correspond to the accumulation of plastic deformation and cracks in the gauge section of a cylindrical dog-bone specimen. Of the first 50 resonance modes that occur, ranging from 3 to 220 kHz, modes classified as longitudinal bending were most sensitive to creep damage while transverse bending modes were found to be largely unaffected. Measure to model comparisons of Δf_R show that the deformation experienced by the specimen during creep, specifically uniform elongation of the gauge section, is responsible for a majority of the measured Δf_R until at least 6.1% creep strain. After 8.8% strain considerable surface cracking along the gauge section of the dog-bone was observed, for which FE models indicate low-frequency longitudinal bending modes are significantly affected. Key differences between historical implementations of RUS for NDE and the FE model-based framework developed herein are discussed, with attention to general implementation of a FE model-based framework for NDE of damage.

1. Introduction

Demand for fast, reliable, and affordable nondestructive evaluation (NDE) techniques for mechanical components has existed for decades [1], with the aerospace industry often at the forefront due to the ever-increasing complexity and cost of turbine engine components [2]. Resonant ultrasound spectroscopy (RUS) falls under the broad field of ultrasonics, and saw early implementations by Fraser and LeCraw of Bell Laboratories in 1964 for measuring elastic properties [3]. However, resonance-based ultrasonic methods often receive less attention compared to pulse-echo, transmission, or phased array ultrasonic methods, especially for NDE of structural and mechanical components. The intent of this work is to demonstrate the utility of a combined framework of RUS measurements and simple finite element (FE) models for NDE of mechanical damage, and to broadly discuss the opportunities and limitations of such a framework as it pertains to manufacturing process control, damage evaluation, and materials science research.

Ultrasonic methods provide the most accurate characterization of elastic properties of solid media [4,5] and they accomplish this through nondestructively propagating low-energy elastic waves through the test specimen. Pulse-echo ultrasonic methods rely on accurately measuring the time required for an elastic wave to propagate through a known volume of material in order to determine the multiple, but at a minimum two, independent elastic wave speeds (c_0) intrinsic to the material. As required by the elastic wave equation [4,6]:

$$c_0 = \sqrt{\frac{C^*}{\rho}}, \quad (1)$$

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where ρ is the density and C^* is an 'effective' elastic constant comprised of a linear combination of C_{ijkl}. These C_{ijkl} define the constitutive relationship between stresses (σ_{ij}) and strains (ϵ_{kl}) in a 3D Cartesian coordinate system as:

$$\sigma_{ij} = C_{ijkl}\epsilon_{kl}. \tag{2}$$

Resonance methods rely on the same fundamental principle outlined in Eq. (1), but instead of time-of-flight measurements resonance frequencies (f_R) of the specimen are used for NDE. In a simplified treatment, the natural vibrational modes of the specimen with free-free boundary conditions are linked to c_0 and the resonance mode wavelength (λ) by:

$$f_R = \frac{c_0}{\lambda} = \frac{n}{2L}\sqrt{\frac{C^*}{\rho}} \tag{3}$$

where dimensions of the specimen geometry: $L = n\lambda/2$ and n is an integer representing mode-order [7]. Even with this simplified treatment, general relationships valuable for NDE can be demonstrated. For example, with all other factors held constant an increase in C^* would increase c_0 and f_R.

Rigorous treatment of the physics described by Eq. (3) requires solving the elastic wave equation in order to yield f_R, often referred to as the *forward problem*. Unfortunately a general analytical solution does not exist for the forward problem [8]. While approximate numerical methods developed by Visscher et al. [9] paved the way to indirect solutions to the inverse problem (calculating elastic properties from measured f_R), Visscher's xyz-algorithm for tackling the forward problem is still limited to relatively simple specimen geometries by the requirement: geometry must be described with a set of continuous polynomial functions [9]. By contrast, FE methods as described by Liu and Maynard [10] rigorously solve the forward problem over simple discretized (finite element) domains that are combined to describe the resonance of simple or arbitrary specimen geometries [10–12]. FE methods, implemented in a straightforward manner by commercial FE modeling packages like Abaqus CAE [13], provide a generalized forward modeling capability that can be combined with RUS measurements of f_R to create a powerful NDE framework. Forward modeling capabilities provide the means to deconvolve multiple concurrent damage mechanisms affecting resonance through one-factor-at-a-time FE modeling studies; while empirical deconvolution via stringent experimental controls is often impractical or impossible.

2. Background

Excitation and measurement of elastic waves for resonance-based ultrasonic methods can be achieved through various means, including: laser pulses [14], magnetic fields [15,16], or contacting piezoelectric transducers [4,6,17,18]. These elastic waves propagate throughout the specimen, reflect off free surfaces, and interfere with one another as they traverse the specimen. Only when the drive frequency of the excitation source nears a natural vibrational mode frequency of the test specimen will two opposite-traveling elastic waves constructively interfere in such a manner as to greatly amplify the deflections imparted by the excitation force, bringing the specimen into a state of mechanical resonance [6]. While all of the RUS measurements collected as part of this study are excited and measured exclusively via contacting piezoelectric transducers, the theory and many of the practical limitations discussed herein also apply to resonance methods that use alternative excitation sources.

In the broader context of ultrasonic methods for NDE, RUS has many advantages over pulse-echo methods. Notable advantages include the potential to fully characterize elastic properties from specimen that are: smaller [4,6,19], irregular in shape [9], or cut with a misaligned crystallographic orientation [20]. Even complex geometry samples are feasible with inclusion of FE methods [10,12], and all from a single broadband measurement [4,6,19]. For a detailed discussion of the merits of RUS as compared to pulse-echo methods, particularly with the aim of accurately measuring elastic properties, the reader is directed toward the works of Heyliger, Ledbetter, and Austin [19], Leisure and Willis [4], and Migliori and Sarrao [6].

A well understood limitation of RUS is the fact that a broadband resonance spectrum contains detailed information about resonance mode frequencies, but little if any information about the resonance mode shape. This limitation is particularly troublesome to efforts evaluating damage or material properties because both endeavors rely on proper mode identification. Laser Doppler vibrometry has been demonstrated as a powerful tool for solving the mode assignment problem by mapping the deflection character of the specimen surface as it resonates [21,14], but is also prohibitively expensive for most NDE efforts. Without additional measurements of mode shape, tracking frequency changes of individual modes will always have a degree of ambiguity; but a strategy for identifying instances of disagreement in mode order between measured and modeled resonance data is discussed in 5.1.

2.1. Historical use of RUS for NDE

RUS-based approaches for NDE to date have primarily focused on comparing a single component to a population of peers—described herein as population statistics sorting (PSS). NDE frameworks based on PSS methods rely on large databases of f_R collected from a population of similar components that are ultimately sorted as acceptable or unacceptable based on prior knowledge of the component history or purposefully imparted damage [22]. Using this teaching set of components with known condition, the f_R landscape is divided into acceptable and unacceptable regimes against which parts with unknown condition are judged. PSS methods are the founding principle behind one commercially relevant NDE with RUS technique: Process Compensated Resonance Testing (PCRT) [23,24]. While commercialized techniques for NDE are still being developed with expanded capabilities, many of the obstacles first encountered by simple PSS methods continue to hinder NDE efforts today. For example, PSS methods are prone to reject components that exhibit anomalous resonance characteris tics—including benign anomalies that may arise from a change in the component manufacturing process [6]. Quantitative correlations between damage accumulation and RUS measurements is often difficult based on measurements alone, and the complex nature of a resonating 3D body can lead to complex changes in resonance with damage [4]. Ultimately these limitations of PSS methods make it difficult to predict how multiple concurrent damage mechanisms will affect resonance, or even how a similar component with slight differences in geometry would behave when subjected to similar damage—requiring systematic damage be conferred to each unique component design in order to create a PSS database necessary for NDE.

Beyond PSS methods that essentially sort components as either acceptable or unacceptable, RUS has been employed for NDE of silicon nitride ceramic ball bearings in a semi-quantitative manner by taking advantage of inherent symmetries [25–27]. The high degree of material and geometric symmetry exhibited by a defect-free ball bearing results in *degeneracy* where multiple resonance modes occur at the same f_R. When damage such as cracks or scratches disrupt the geometric symmetry of the bearing, *degenerate-mode splitting* is observed in the RUS spectrum. Degenerate-mode splitting occurs because the f_R of certain modes are affected by damage to a greater extent than others modes,