



# Absorptive viscoelastic coatings for full field vibration coverage measurement in vibrothermography



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## ABSTRACT

Vibrothermography is a rapidly emerging nondestructive evaluation technique for detecting fatigue cracks in aircraft components. Externally applied mechanical vibrations in a specimen generate crack heating between vibrating crack faces due to friction or other irreversible phenomena. Crack heating in vibrothermography depends on the vibrational stresses, and therefore the amount of vibration generated in the specimen. A method to measure the vibration distribution from the hysteretic heating of viscoelastic polymer adhesive applied to a specimen surface is described. The heat generated by the adhesive coating maps directly to the vibrational strain distribution in the substrate. This is a fast method of vibration coverage measurement for vibrothermographic testing.

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## 1. Introduction

Vibrothermography is a nondestructive evaluation method for finding cracks in aircraft components by vibration induced heating. This method is effective in finding surface cracks in aircraft components like turbine blades, and turbine disks and subsurface cracks such as delaminations in composite panels [1–3]. When a specimen with a crack is subjected to mechanical vibrations, friction or other irreversible phenomena between rubbing crack faces generate heat, which can be detected by an infrared camera. Several mechanisms have been proposed to cause crack heating, but friction has long been suspected to be the dominant mechanism of crack heating in vibrothermography [4]. Vibrations are usually generated using a broadband piezoelectric transducer or an ultrasonic welder/horn assembly [5,6]. The amount of heat generated by the crack depends on the dynamic vibrational strain and excitation frequency [7] and hence a quick and easy way to measure dynamic strain is important. Since the specimen vibrates primarily in resonant modes, the vibration pattern is not uniform but arises from the combination of the mode shapes of the excited modes, resulting in regions of high and low vibrational amplitude. Therefore, to be able to predict how easily detectable a crack at a

particular location will be when vibrated, we must know the vibration distribution in the specimen. The existing methods of full field dynamic vibration measurement are either too time consuming or are not practical for application in vibrothermography. Strain gages are good for point measurement but covering the entire specimen with strain gages in order to get full surface strains is highly impractical. Laser velocimetry method [8], which is dynamic and non-contact, can be used to evaluate mode shapes when used with a repeatable source. However, this will require scanning the entire specimen surface using three laser vibrometers simultaneously to get the full 3D vibration field and is time consuming to set up the experiment and error prone. Other optical and interference based methods such as holography can measure mode shapes but are expensive and generally presuppose harmonic excitation, as opposed to the multifrequency “chaos” excitation that is commonly used industrially [9,10]. Finite element based methods are also time consuming and typically are unable to accurately model the complicated transducer-specimen coupling, and up until now, have not been very accurate for modeling the vibration [11].

In this paper, we propose a method of vibration distribution measurement for vibrothermography using viscoelastic absorptive coatings. We define the term ‘vibration coverage’ to describe how completely the vibration is distributed in the specimen. Ideally, vibration coverage is a quantitative mapping between the dynamic strain on the specimen surface and the resonant mode shapes of the specimen for a given vibrothermographic excitation. Having

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the knowledge of vibration coverage for a given specimen configuration enables one to determine the relative signal expected from a crack in the regions of interest in that test configuration. Practitioners have used tapes and adhesives as qualitative indicators of vibration for a long time, but no procedure for measuring vibration coverage has been reported so far. Quantitatively determining the vibrational strain across the entire specimen surface will be a critical step for performing crack detectability and probability of detection studies for vibrothermography. In this paper, we measure vibration coverage by applying an absorptive adhesive coating to the specimen surface and observe the heating of this coating when the specimen is vibrated. We quantitatively correlate the vibrational strain in the specimen with the temperature rise in the adhesive coating for a simple rectangular bar geometry. Extrapolation of these results to more complicated geometries can be used to achieve qualitative mapping of vibration coverage.

## 2. Absorptive viscoelastic coatings

Viscoelastic materials are a class of materials that exhibit both viscous and elastic nature. When subjected to a load, the relaxation effects inside the material cause the deformation to lag the applied load, resulting in hysteresis. These materials are modeled as having complex Young's modulus  $E^* = E' + jE''$  that is a function of temperature and frequency [12]. The real part of the modulus, called storage modulus ( $E'$ ) is equivalent to the Young's modulus of purely elastic materials and it determines the in-phase elastic strain in the material. The imaginary part, called loss modulus ( $E''$ ), determines the out-of-phase (viscous) component of strain. The quantity  $\delta \equiv \arctan(E''/E')$  is the phase angle between stress and strain,  $\delta$  being  $0^\circ$  for elastic materials,  $90^\circ$  for viscous materials and  $0^\circ < \delta < 90^\circ$  for viscoelastic materials. The frequency dependent modulus,  $E$ , can be measured experimentally using dynamic mechanical analysis [13]. When a viscoelastic material is subjected to oscillatory loading, stress in the material leads the strain and the viscous relaxation, represented by the imaginary part of the Young's modulus is determined by the strain rate. In this loading, only a fraction of the energy applied to the material is recovered at the end of the cycle and the rest of it is dissipated as heat [14]. This behavior is analogous to an AC circuit in electrical engineering [15]: stress and strain in the material are complex exponentials analogous to voltage and current. The recovered energy after one cycle is analogous to reactive power and the dissipated heat is analogous to real power. The ratio of energy dissipated to energy recovered is determined by the value of  $\tan \delta$ , which is analogous to the power factor of an AC circuit.

When an elastic specimen undergoes a cyclic excitation, the specimen responds in phase with the loading and all the energy stored in the specimen during the positive half cycle of loading is released during the negative half cycle. Therefore, the net energy dissipated during the vibration cycle is zero. However, if the same specimen is coated with a layer of viscoelastic material and is again subjected to the same cyclic loading, the specimen does not respond in phase with the applied load and all the energy is not restored in the material at the end of the cycle; a part of it is dissipated as heat. This delayed viscous relaxation creates hysteresis in the specimen. The thermal power dissipated per unit volume ( $g$ ) due to hysteresis is calculated by evaluating the integral:

$$g = \sum_i \frac{1}{\tau} \int_{\tau} \frac{1}{2} \sigma_i \dot{\epsilon}_i dt \tag{1}$$

where  $\tau$  is the time period of oscillation and the summation index  $i$  is over all the components  $\sigma_i$  and  $\epsilon_i$  of the stress and strain tensors respectively. Dot indicates time derivative. If the loading or

deformation is uni-axial, all but one term in the above summation vanish and the integrand contains the only nonzero stress or strain corresponding to the loading axis. Based on the above relation, when the axis of stress or deformation is known, the thermal power dissipated by the coating can be used as a metric to quantify the dynamic vibrational strain in the substrate. For a generalized multi-axial loading, evaluation of the above summation over all stress and strain components can be simplified by the use of the first and second strain invariants  $J_1 = \text{tr}(\epsilon)$  and  $J_2 = \frac{1}{2}(\text{tr}(\epsilon^2) - \text{tr}(\epsilon)^2)$  [16]. In this case, thermal power only is not adequate to quantify both the strain invariants as it would be an ill-conditioned problem. We suggest that using at least two independent measurements i.e., absorptive coatings and another independent strain measurement method (like photo-elastic coatings that calculate the difference of principal strains [17]) would solve this problem and quantify the strain invariants for more general multi-axial loading. In this paper, we measure dynamic strains for uni-axial loading of a rectangular bar only and give a qualitative vibration coverage analysis for generalized multi-axial loading in a more complex geometry.

To quantify vibration coverage, we test rectangular bar shaped metal specimens at flexural resonant frequencies. In a flexural resonance, the axial strain at the surface of the substrate is much higher than all other strain components and hence the loading becomes effectively uni-axial (neglecting all other strain components). The integral of Eq. (1) for the case of axial loading becomes:

$$g = \frac{1}{\tau} \int_{\tau} \text{Re} \left( \frac{1}{2} \sigma \dot{\epsilon}^* \right) dt \tag{2}$$

where  $\epsilon = \epsilon_0 e^{j(2\pi f)t}$  is the dynamic cyclic strain in the longitudinal direction,  $\epsilon_0$  is the strain amplitude,  $t$  is the time,  $\tau$  is the time period of excitation and  $f = 1/\tau$  is the excitation frequency in Hz. The asterisk symbol indicates complex conjugate. Substituting Hooke's law for stress  $\sigma = \epsilon(E' + jE'')$ , the integral becomes

$$g = \frac{1}{\tau} \int_{\tau} \text{Re} \left( \frac{1}{2} (E' + jE'') \epsilon \dot{\epsilon}^* \right) dt \tag{3}$$

Replacing the strain derivative  $\dot{\epsilon}$  by  $j\omega\epsilon$  for cyclic loading and evaluating the above integral gives the thermal power  $g$ . If the substrate has no adhesive layer on it, the Young's modulus is purely real ( $E''$  is zero) and the thermal power in the integral evaluates to zero. With the coating applied, however, the dissipated power is

$$g = \pi E'' \epsilon_0^2 f \tag{4}$$

We model strain in the coating as determined by strain on the surface of substrate. Therefore, from Eq. (4), by measuring the thermal power dissipated by a coating with a known loss modulus at a known vibration frequency, we can quantify the vibrational strain in the coating. Following our model, this strain is the same as that on the surface of the metal bar. The thermal power dissipated by the coating is a measure of vibrational strain coverage in the substrate underneath.

Temperature rise in the coating increases with loss modulus and coating thickness. However, substantially thicker coatings shift the resonance frequencies of the specimen due to the added mass and therefore do not represent the specimen's natural resonance behavior. Also, our assumption that strain is uniform across the thickness of the coating ceases to be valid if the thickness becomes comparable to that of the substrate or is not much smaller than the lateral feature size. On the other hand, coatings that are too thin do not respond to low strain amplitudes and do not dissipate detectable amount of heating. Adding multiple layers of thin coatings increases the heat generated.

Since temperature rise is a more directly measurable quantity than the thermal power, we can rewrite Eq. (4) in terms of peak

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