IMAGING OF MECHANICALLY INDUCED THERMAL HEAT PATTERNS

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ABSTRACT

Imaging information obtained from nondestructive tests is becoming more widely investigated and developed. Imaging obviously has the potential to provide a more easily interpreted outcome of a nondestructive test, leading to more rapid and correct evaluation of the state of the examined material. This work presents one aspect of the field of imaging -- developing a thermal image of the surface of a material subjected to mechanical vibrations. The technique of vibrothermography has been under investigation in our laboratory for several years, especially as applied to advanced composite materials. We will present in this paper a review of the imaging aspects of the technique, in particular discussing the phenomena responsible for producing a surface heat pattern and the phenomena responsible for obtaining a suitable image of this pattern. Finally, a discussion is given of the possible interpretations which may be made from the image concerning evaluation of the material condition, as may be used in a nondestructive evaluation procedure. Examples will be drawn from a number of tests performed in our laboratory.

INTRODUCTION

Thermography is the measurement and presentation of the isothermal contours existing on the surface of an examined object (if the object is solid) or the averaged isothermal contours through a volume of an object (if the object is fluid). If an object is in thermal equilibrium with no internal physical or chemical processes occurring, then the temperature will be uniform and there will be no useful information to be gained from thermography. However, if a physical or chemical process is occurring, one might be able to learn much about the process and the internal state of the object by applying thermography to it. For example, thermography has been used to detect cancer of the breast since cancerous tissue generates more heat than surrounding normal tissue. Thermography has been used to study the down-range motion of exhaust clouds from rockets by detecting the exothermic chemical reactions in the clouds which continue long after the rocket has left. It has been used to detect flaws in electrical circuits and transformers by measuring the abnormal heats developed by the flaws when electrical current is passing through the electronic components. It has also been used for detecting defects in solid materials. The latter use of thermography is the major area of interest to be covered in this paper.

For the nondestructive investigation of defects in solid materials, thermographic techniques can be classified into two general types -- active and passive. Passive techniques generally refer to those methods which develop temperature gradients by application of heat externally to the solid body. The external heat is applied by conducting heat into or out of the body by direct contact with a hotter or colder body, respectively; by radiating the heat into the body from an external heat source; or by convecting the heat across the surface of the body through hot air fans, etc. The externally applied heat will be conducted through the body and any defected region will develop temperature gradients in the vicinity of itself because of local differences in the thermal conductivity of the material. The thermal gradients are then observed by any of several different temperature detection devices.

Active thermographic techniques are those methods which develop heat internally through the action of internal mechanisms as a result of various physical or chemical phenomena. For example, electrical current develops Joule heating in a solid body due to its resistance. If one region of a body is inhomogeneous or for some other reason has a local difference in electrical resistance, a local temperature gradient will be established which can be detected thermographically. As another example, when mechanical vibratory energy is applied to a solid, some fraction of the mechanical energy is transformed into heat by any of a number of nonlinear, irreversible loss mechanisms. Defects or other mechanical inhomogeneities will develop thermal gradients in their vicinity because of their different mechanical properties and hence their differing rates of heat generation. The emphasis in the remaining portion of this paper will be placed upon the mechanical generation of heat for thermographic techniques since the major interest in our laboratory has been the mechanical characterization of materials. It appears reasonable to assume that the detection of mechanically generated heat will be more pertinent to mechanical characterization than heat generated by other physical mechanisms or even than that heat detected by passive methods.

In the next section, various heat producing mechanisms which can account for the transformation of mechanical energy into thermal energy are discussed. Following that is a brief discussion of several methods currently in use for imaging the detected thermal patterns. Finally, several examples from the author's own experience are used to illustrate the application of the thermography to composite materials.

HEAT PRODUCING PHENOMENA

As noted in the previous section, active thermographic techniques use the production of heat via internal mechanisms to establish temperature gradients which can be detected on the surface of a solid body. The heat is produced by any number of physical phenomena. As an example, electrical energy is converted to heat through Joule resistance heating. Regions of varying electrical resistance can be identified through development of temperature gradients on the surface. Magnetic induction may also be used as an electromagnetic means for the generation of internal heating. For the purposes of this paper, we will henceforth discuss only active thermographic techniques which use mechanical vibratory energy to produce thermal gradients through various dissipative and energy conversion mechanisms.

To begin our brief discussion, there are a number of anelastic effects which can account for the generation of heat when low amplitude levels of mechanical vibratory energy are applied to a solid body. These anelastic mechanisms include such things as atomic diffusion, order-disorder processes, thermal diffusion, etc. The latter mechanisms are often referred to as relaxation phenomena since they are highly frequency dependent and disappear as the frequency increases past the range of their active influence. For the study of solids, anelasticity has developed mainly as a special part of the subject having to do with physical and chemical phenomena in crystalline solids. The object of this development has been mainly to study the material itself as a bulk substance, and to establish the character of certain internal features by their relaxation spectra. For most purposes, the generation of heat necessary for the nondestructive evaluation of solids requires significantly larger amounts than can be accounted for by most of the dissipative mechanisms associated with anelastic phenomena. Also the range of stress applied, as well as the range of mechanical vibration frequency used, for mechanical characterization is usually above the low levels for which anelastic dissipative effects are a significant contribution to the heat developed. For these regions, anelastic dissipative effects are normally ignored when discussing thermography.

Viscoelasticity is a more general field of study in solids and applies more closely to situations where the inherent response of a material to an applied state of stress or strain is rate dependent. Viscoelastic damping mechanisms include such phenomena as grain boundary or phase boundary effects, eddy current effects, and various molecular motions in long-chain molecule materials. The latter is especially important as a possible heat producing mechanism in polymer matrix composites.

Thermoelasticity is a type of anelastic effect which is present if the mechanical excitation frequencies are high enough. Under normal quasi-static rates of strain, the mechanical process is isothermal. When the rate of straining is high enough, the strain process approaches an adiabatic process. When mechanical vibrations are applied, the strain rate lies between that of an isothermal and an adiabatic process. In any case, the mechanical energy losses are proportional to the difference between the adiabatic and isothermal elastic compliances, which for many solids is of the order of 10-15%. The thermoelastic effect is normally quite small also, but if appropriate procedures are used, it can be employed to determine the sum of the principal stresses at each point of the surface of the solid. This phenomenon, in fact, is the basis of a commercially available thermographic system for the measurement of the principal dilatation.

For the nondestructive inspection of composite materials, experience has shown that there is a combination of viscoelastic and friction dissipative mechanisms which are responsible for generating the heat detected thermographically [1-4]. The friction effects have not been well characterized, but there is sufficient experimental evidence to show that internal delaminations and cracks in composites can produce significant heating by surface interaction at certain frequencies corresponding to local mechanical resonances [5,6].

THERMOGRAPHIC IMAGING TECHNIQUES

The imaging of thermographic patterns has evolved considerably in the last two decades. Basically, there are two ways that temperatures can be measured on the surface of a solid body -- contact methods and non-contact methods. Contact methods include all those techniques which require physical contact with the surface of the material by the temperature sensor. These methods include surface coatings such as temperature-sensitive paints, phosphors and papers, liquid crystals, and thermochromic order-disorder compounds. Contact methods have the major advantages of being inexpensive and relatively easy to apply. However, they have some major disadvantages, including being sensitive only to a very narrow range of temperatures. The temperature of interest must be known beforehand and the coating manufactured accordingly. Also, the paints and papers undergo an irreversible reaction at the critical temperature and hence can be used only once. Liquid crystals have critical temperatures which are very sensitive to chemical composition and which can be altered with time by the environment. For serious nondestructive evaluation studies, noncontact imaging methods based upon the detection of infrared radiation are almost a necessity.

As already noted, thermographic imaging has evolved considerably in the last two decades because of the commercial development and availability of real-time video thermographic cameras. These systems use semiconductor materials which are infrared sensitive at low temperatures and various combinations of rotating scanning mirrors to produce pictel elements which can be displayed electronically upon a cathode-ray tube. Picture displays can be continuous gray scales or selected color scales.

As is well known, every body radiates thermal energy in the electromagnetic spectrum (infrared) at temperatures above absolute zero. The intensity of radiated energy is uniquely determined by the temperature of the radiating surface. The intensity is modified by the degree to which the surface deviates from a black body radiator. A black body radiates the maximum amount of energy consistent with its temperature while all real bodies emit a fraction of this energy depending upon the surface characteristics. The fraction of energy emitted depends upon a quantity called the surface emissivity. If the surface is prepared with a nonreflective coating, the emissivity can be brought reasonably close to one. In any case, for most nondestructive testing purposes, one is interested in temperature gradients and not the absolute value of temperature at each point of the surface.

IMAGE INTERPRETATION

Real-time video thermography has been used to nondestructively evaluate damage in composite materials in our laboratory. We have coined the terminology vibrothermography to apply to the application of mechanical vibrations to a specimen for the purpose of generating heat which can be detected thermographically. Generally, the mechanical vibrations are of one of two types: large amplitude and small frequency (such as occurs in a fatigue test) or small amplitude and high frequency (such as occurs in a mechanical shaker). The mechanical vibrations are preferentially transformed into heat at regions of discontinuities or defects, creating higher temperatures and gradients which are easily detected by video thermography.

During fatigue testing, we have observed in our laboratory that the early detection of damage in composites is easily accomplished by video thermography [7]. Very early in the fatigue lifetime, local regions develop higher temperatures where, because of local material condition, damage is developing on a microscopic scale. It has been our experience that these "hot spots" are early predictors of damage which eventually often develops to the point that the material fails at these locations. The early appearance of these hot regions appears to be caused by stress concentrations existing around local material flaws which cannot be detected generally by other nondestructive test methods. Figure 1 is an example of the early detection of a hot region in a helicopter blade which was undergoing fatigue testing. After many millions of cycles above the design lifetime, the blade eventually broke at the region of the hot spot which was thermographically detected very early in the fatigue test.

Figures 2 and 3 are examples of an analytic calculation and a thermographic picture, respectively, of an edge delamination in a graphite epoxy laminate. The laminate had been fatigue tested, but Fig. 3 was made by inertially loading the specimen in a mechanical shaker and vibrating it at low amplitudes and approximately 18 kHz. The calculation was performed to determine the expected surface heat pattern resulting from a subsurface heat source when the anisotropic thermal conductivities of the individual laminae are taken into account. As can be seen by comparing Figs. 2 and 3, the actual surface heat pattern resulting from two neighboring delaminations is closely predicted analytically. More details can be found in Ref. [8].

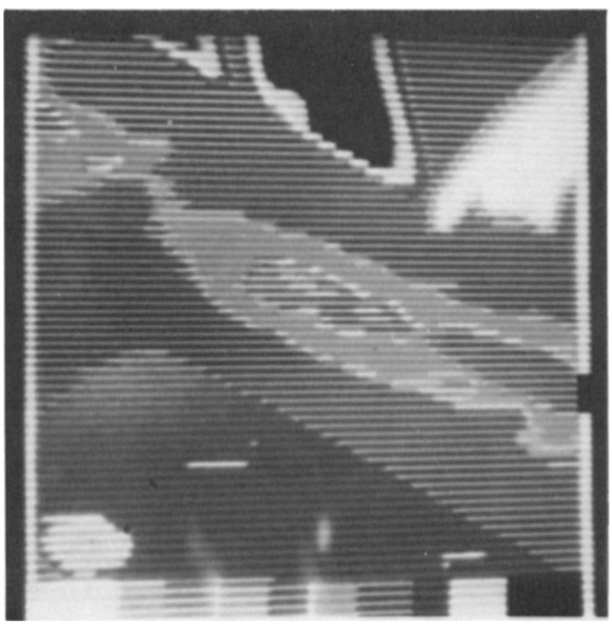

Figure 1. Thermograph of helicopter rotor during fatigue test. (Technician's hand is pointing to area which is heating due to developed damage.)

The heat developed during mechanical vibration at high frequencies appears to be a result of local resonances of the material surrounding flaws such as delaminations [6]. A delamination can be thought of as being surrounded by two plates, each having the size of the delamination and the thickness of the laminate above and below the delamination, respectively. When appropriate boundary conditions are imposed upon these delamination-sized plates, the natural modes of vibration for these

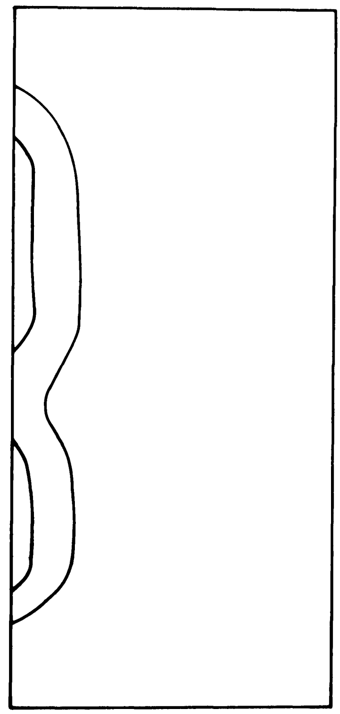

Figure 2. Analytic calculation of predicted surface heat pattern due to subsurface heat sources.

small plates can be determined. As one sweeps through a range of mechanical frequencies on the shaker, hot spots appear and disappear at the delamination sites as a function of frequency. The frequencies at which the hot spots appear correspond to the natural modes of vibration of the delamination-sized plates. Figure 4 is an example of a hot spot occurring at a delamination which was simulated by manufacturing a 1/5 in. (1.1 mm) square piece of mylar in the center of the graphite epoxy laminate during lay-up of the laminate. Table 1 illustrates the calculated natural modes of vibration and the frequencies at which the hot spots were experimentally observed.

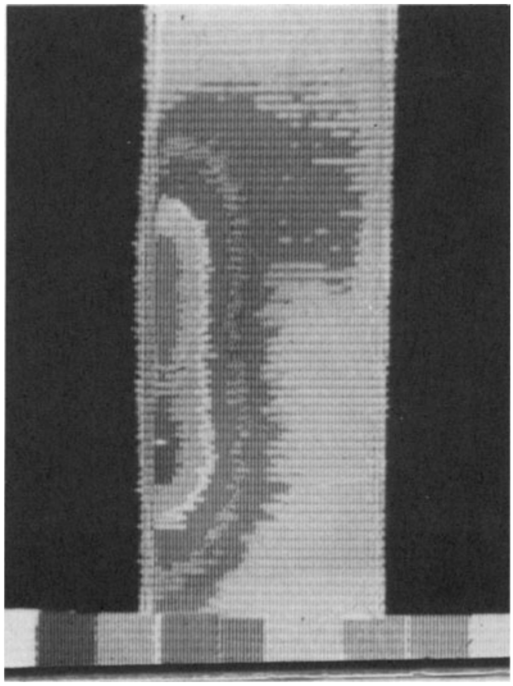

Figure 3. Vibrothermograph of composite edge delaminations.

Table 1. Calculated and Experimentally Observed Frequencies for Heating

Mode	Analytically Predicted Frequency	Experimentally Observed Frequency
1	10.0 kHz	10.2 kHz
2	13.0 kHz	13.0 kHz
3	19.4 kHz	18.35 kHz
4	26.2 kHz	26.1 kHz

SUMMARY

The imaging of surface temperatures on the surface of a solid body via the technique of thermography is a useful one for nondestructively characterizing the mechanical condition of a material. This paper has reviewed very briefly the phenomena which produce heating during mechanical vibration of a solid and the means for imaging the surface temperature patterns. Finally, several examples were presented for the nondestructive evaluation of composite materials by this method.

ACKNOWLEDGEMENT

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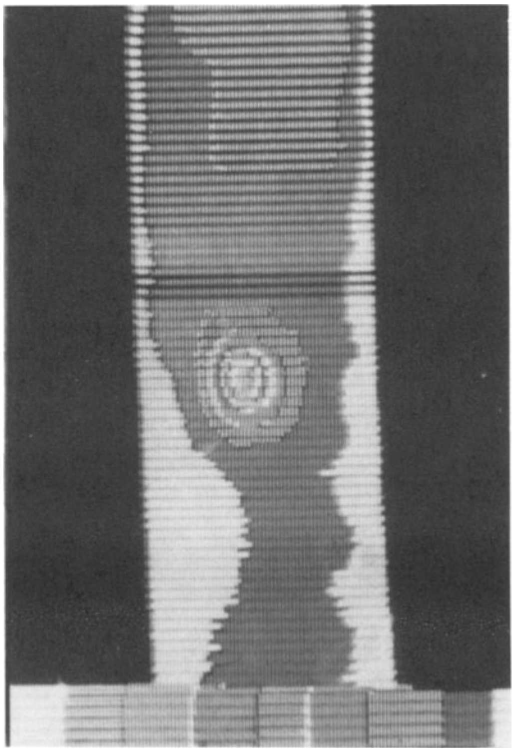

Figure 4. Vibrothermograph of composite with 1/5 in. (1.1 mm) square delamination (simulated by placing mylar square in specimen during fabrication).

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