FIRST MEASUREMENTS FROM A NEW BROADBAND VIBROTHERMOGRAPHY MEASUREMENT SYSTEM

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ABSTRACT. We report on the construction and development of a broad-spectrum vibrothermography (Sonic IR) measurement system at the Center for NDE. The new system uses a broadband actuator instead of an ultrasonic welder to generate vibration and induce heating of cracks. A high-resolution infrared camera captures the IR signature of a crack, and a reconfigurable data acquisition software system acquires and processes the IR images and vibrometry waveforms in real time. We present and discuss results from initial experiments with this system, including the frequency dependence of vibrothermographic heating of flaws in a jet turbine stator vane and an analysis of the correlation of heating with vibration frequency in a cracked test specimen.

Keywords: Vibrothermography, Sonic IR, Sonic Infrared, Crack Detection
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INTRODUCTION

Vibrothermography is a very promising nondestructive testing method for finding surface and near-surface cracks and flaws. A specimen is vibrated at high amplitude and heat generation is observed around cracks, typically with an infrared camera. The method was originally developed by Henneke et al. [1, 2], and more recently rediscovered, optimized, and popularized by Favro et al. [3]. Vibrothermography, also known as sonic infrared ("Sonic IR"), is widely proposed as a possible replacement for fluorescent penetrant testing. Key advantages include the prospect for faster measurements due to the imaging capabilities of infrared cameras combined with automatic image processing for defect identification. Despite the promise, substantial questions remain because many aspects of the underlying physics remain poorly understood. The most widely accepted explanation for the crack heating phenomenon is frictional heating caused by motion of the crack faces. It has also been proposed that plastic deformation at the crack tip can contribute to the observed heating. Since vibration patterns and mechanical resonance effects are fundamentally dependent on geometry, methods for estimating reliability and probability-of-detection (POD) that take vibration patterns into consideration need to be developed. Finally concerns about potential damage to parts caused by the high-amplitude vibration need to be addressed.

The Center for Nondestructive Evaluation at Iowa State University has built a new research program in vibrothermographic nondestructive testing to study the vibrothermography process and answer some of these questions. In this paper, we review the development and progress of developing a new measurement system for vibrothermography, and present some initial results.

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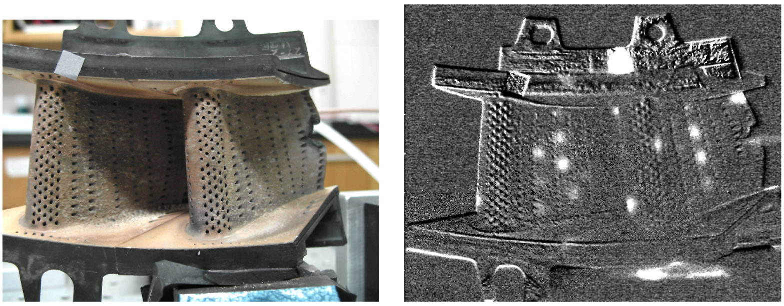


(a) (b)

FIGURE 1. (a) Visible light image of turbine stator vane. (b) Infrared image of vibrothermographic heating of vane with background subtraction.

SYSTEM DESIGN

The components of a typical vibrothermography measurement system are an ultrasonic welder to generate vibration, an infrared camera to record the heat generated around cracks, and a laser vibrometer to monitor the vibration. A computer with custom software is used to acquire waveforms and images, and some systems also include motion control. Our system is similar, except instead of an ultrasonic welder as a vibration source we use a simple piezoelectric stack driven by a power amplifier fed by arbitrary waveform generator. The piezo stack has a resonant frequency above the 1 kHz – 20 kHz range we primarily use for excitation, so it gives a reasonably broadband frequency response over that range. As a result, instead of using narrowband excitation and relying on the tip-specimen nonlinearity to generate a broad spectrum of excitation frequencies, we can generate that broad spectrum directly with our transducer. The excitation waveform is typically a frequency sweep (chirp) waveform.

Our system is controlled by a newly designed data acquisition software package “dataguzzler”. This software is not specific to vibrothermography, but is of more general utility for high-performance laboratory waveform and image acquisition. It is designed to be reconfigurable to adjust to the changing needs of a dynamic laboratory, and is based on prototype software previously used at ISU for air-coupled ultrasonics and spacecraft leak location. Among other things, this package can do real-time processing of the acquired images and waveforms, including averaging, cross-correlation, spatial and temporal Fourier transforms, and calculus operations. ISU expects to publish this software soon as open source in the hope that it will be of use to other research groups, at the URL http://ahab.cnde.iastate.edu/ sdh4/dg_web/.

PRELIMINARY RESULTS

Figures 1a and 1b show a visible light image and a vibrothermographic heating image respectively of a turbine stator vane. The vibrothermographic image has the background subtracted out so that it only shows heat generated at at flaws and coating delaminations (in addition the outline of the entire part is visible because the part moved slightly in the fixture during acquisition). At least fifteen indications are observed, most of which are probably delaminations of the thermal barrier coating. The strong indication in the upper right corner is almost certainly a crack, and the indication at the top may be either a flaw in the weld joint

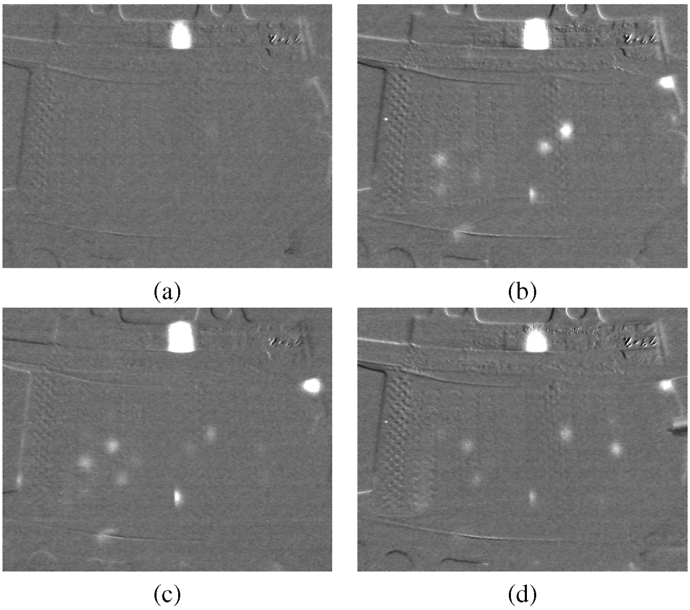


FIGURE 2. Vibrothermographic heating of stator vane in response to excitation at (a) 10 kHz, (b) 10.2 kHz, (c) 10.4 kHz, and (d) 10.6 kHz.

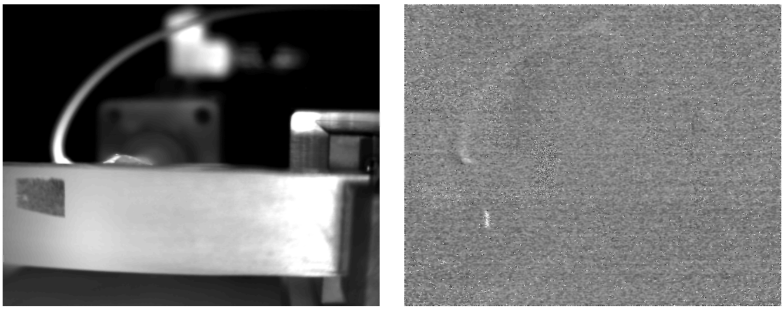
that attaches the two vanes to each other, or it may be a dry contact next to the weld that heats in response to vibration.

Our broadband excitation system can also operate in a narrowband mode simply by programming it with a narrowband tone-burst waveform instead of with a frequency sweep. Figure 2 shows the effect of exciting this same specimen at different tone-burst frequencies. The four images (a), (b), (c), and (d) show the infrared heating in response to excitations at 10 kHz, 10.2 kHz, 10.4 kHz, and 10.6 kHz respectively. We observe that different patterns of flaws are seen for the different excitation frequencies. The 10 kHz excitation, for example, indicated only the weld at the top and none of the other flaws. The nature of the vibration is a controlling parameter of the vibrothermographic measurement, and based on these data we conclude that to ensure reliable defect detection a better understanding of the vibration processes will be necessary.

Even with our relatively low-power excitation system, at times we still see substantial tip-specimen nonlinearity that generates harmonics and subharmonics of the excitation frequency. In order to look at the dependence of crack heating on frequency, we need to relate the heating of the crack to the frequencies of vibration of the specimen rather than the frequency of the exciter.

We can define a crack-heating sensitivity coefficient $x(f)$ that represents the tendency of a particular crack to heat in response to vibration at frequency f, as measured at a single point with a laser vibrometer. We represent the total heating of the crack H in response to a single excitation as an integral of the sensitivity coefficient times the absolute square of the Fourier transform of the measured velocity at one point of the specimen, $v^2(f)$:

$$H = \int x(f) v^2(f) df \tag{1}$$



(a) (b)

FIGURE 3. (a) Infrared image of test specimen. (b) Infrared image of vibrothermographic heating of test specimen with background subtraction.

Because of the tip-contact nonlinearity the actual vibration, as measured by the laser vibrometer to be $v(f)$, in general contains a series of harmonic and sub-harmonic frequencies. For this reason, in order to find $x(f)$ we need to run a series of experiments with different excitations. Then the data resulting from those experiments can be inverted to find the correlation of crack heating with vibration frequency, $x(f)$.

If we discretize $x(f)$ and $v(f)$ in frequency, we can rewrite H as

$$H = \sum_j v_j x_j, \tag{2}$$

where j is the index over frequency. If the experiment is repeated n times, with $i = 1..n$ being the experiment index, then we can write

$$H_i = \sum_j v_{ij} x_j. \tag{3}$$

Equation 3 is recognized as a matrix multiplication

$$\underline{H} = \underline{\underline{V}}\,\underline{X}. \tag{4}$$

Therefore $\underline{X}$ can be estimated by inverting the matrix $\underline{\underline{V}}$. To do this, we reduce the number of frequencies in v_j by grouping adjacent frequencies, and then invert $\underline{\underline{V}}$ using a least-squares algorithm. A cracked test specimen and the heating of the crack in response to vibration are shown in Figs. 3a and 3b. We applied a series of 125 tone burst excitations to this specimen, with frequencies from 200 Hz to 25 kHz, and we recorded the infrared heating of the crack $\underline{H}$ along with the vibration of the specimen $\underline{\underline{V}}$, as measured with a laser vibrometer. Finally, we calculated an inverse (using the singular value decomposition) of $\underline{\underline{V}}$ and used this inverse to estimate $\underline{X}$, the sensitivity (or correlation) of the crack heating phenomenon to the frequency and amplitude of measured vibration of the specimen. The sensitivity coefficient $\underline{X}$ is plotted in Fig. 4 using a solid line and shows a very strong correlation of crack heating with the presence of 19 kHz vibration and near zero correlation with other frequencies. The dashed line in Fig. 4 shows the measured infrared signal from the crack as a function of *excitation* frequency. Because of the tip-specimen nonlinearity generating additional frequencies, excitation frequency does not correlate nearly as well with crack heating as vibration frequency. Repeating the experiment yielded nearly identical results. The observed sensitivity to 19 kHz

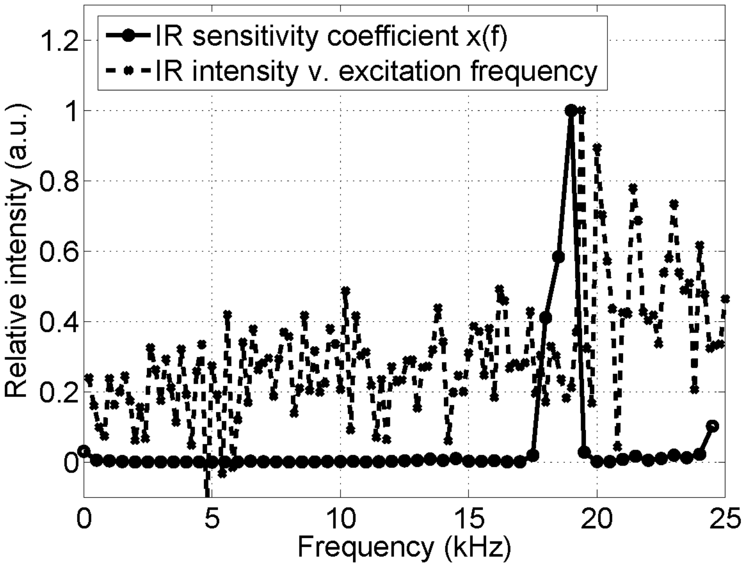


FIGURE 4. Sensitivity of the crack heating process to vibration frequency and excitation frequency.

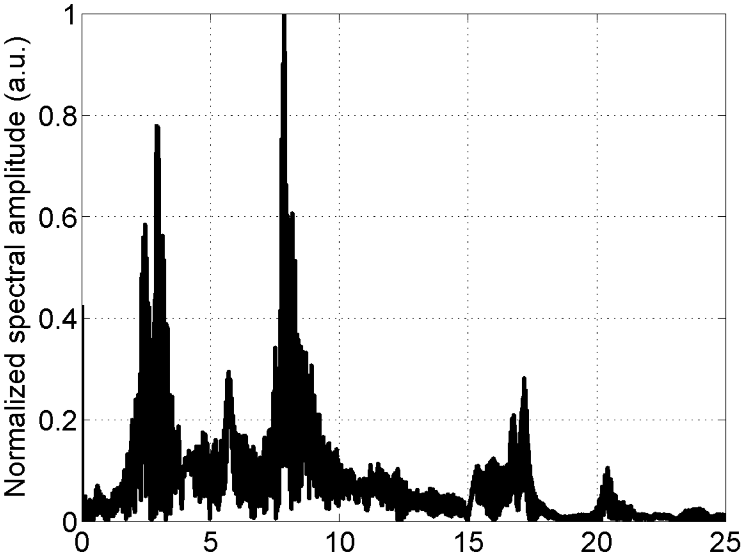


FIGURE 5. Spectrum of the measured vibration in response to a broadband (200 Hz–20 kHz) chirp.

is, of course, specific to the particular test specimen in the particular geometry and method of excitation under test. Nevertheless, it suggests that some particular mode of vibration of the specimen dominates the crack heating process in this case.

Curiously, if we apply a broadband chirp excitation (frequency sweep) to this sample, we see the pattern of resonances given in Fig. 5, which does not indicate a resonance at 19 kHz. Perhaps the mode that excites the crack is a very low Q resonance or perhaps its motion is largely normal to the direction of vibrometer sensitivity. It is not entirely clear to us at this time why the crack heating in this case correlates so strongly with an apparently non-resonant frequency.

We have demonstrated the ability of our system to find cracks in both test specimens and actual turbine components. The heating of a crack, as measured by its infrared response, seems to correlate very strongly with the frequencies of vibration of the specimen, which may be different from the vibration of the actuator. Broadband excitation helps to ensure that a wide range of frequencies are excited in the part, and therefore that cracks which respond to any of those frequencies will heat up.

ACKNOWLEDGMENTS

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