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FREQUENCY DEPENDENCE OF VIBROTHERMOGRAPHY

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ABSTRACT. It has long been postulated that vibrothermographic heating – the heating of cracks due to sound or vibration-induced rubbing - may be frequency dependent. It has been difficult to factor out the innate frequency dependence of the heat-generation process from the geometry-dependent mode structure. We present experiments showing the heating of cracks in slender Inconel/Titanium specimens at transverse resonance. Different resonant modes vibrate at different frequencies but load the crack in the same way (Mode I). The results show a clear increase of heating with vibration frequency.

Keywords: Vibrothermography, Sonic IR, Thermosonics, Frequency Dependence

PACS: 43.40.+s, 81.70.Cv, 87.63.Hg

INTRODUCTION

Vibrothermography is based on the fact that when vibrated, heat is generated due to the friction of the crack asperities. Traditionally, specimens are excited at a fixed frequency, for example, 20 KHz or 40 KHz with an ultrasonic welder [1]. However, the ultrasonic welder system relies on nonlinearity and acoustic chaos, therefore it is not repeatable and probability of detection is difficult to predict [2]. Instead, we use a bare piezoelectric stack as a vibration source, which is less efficient at transmitting sound energy transmitted into the specimen, but can generate both broadband (frequency sweep) and narrow band (tone burst) excitations [3]. When excitation frequency is tuned to match the natural resonance frequencies of the specimen, the state of strain/stress in the specimen can be calculated from the known mode shape and measured vibration amplitude [4].

The frequency dependence of vibrothermography (thermosonic effect) has been discussed previously [5]. Because of the fixed frequency excitation system, vibration of the specimen could not be fully controlled, therefore no quantitative relations were provided. We present our experiments in this paper, showing that for the same dynamic stress (Mode I loading) around the crack, higher resonance frequencies indeed generate more heat than lower resonance frequencies, and quantify the effect by statistical models.
EXPERIMENT

Fifteen specimens with real fatigue cracks and one specimen with viscous-material filled (VMF) synthetic defects were used in the experiment [6]. Each specimen was mounted carefully at the nodal points of the desired flexural resonance mode. A piezoelectric transducer was pushed against the center of the specimen. For these fatigue specimens, only odd modes were used, while for the specimen with synthetic defects, both odd and even modes were used.

A laser vibrometer was pointed at a known location of the specimen, measuring the out-of-plane velocity of that point. Dynamic stress in this vibrating slender bar was then calculated using elementary theory of flexural vibration from the known amplitude and mode shape. The calculation is based on the assumption that the specimen is under free transverse vibration. Scanning the surface motion profile with the vibrometer showed that the influence of the transducer and mounting to be almost negligible.

The surface temperature profile was measured by a calibrated infrared camera. The temperature rise was calculated from the peak value after a surface fitting of the temperature profile. In order to randomize the effect of test order, excitations of different amplitudes were performed in a pre-determined random order.

RESULTS AND DISCUSSIONS

The surface motion profile was measured for each specimen, in order to verify free vibration condition. Figure 1 shows the mode shapes for 3rd, 4th and 5th order flexural modes for one of the specimens with fatigue cracks. The experimental and theoretical mode shapes agree extremely well with each other, which indicates that: 1) the specimen is indeed vibrating at the desired resonance mode; 2) calculation of dynamic stress is valid.

Figure 2 shows the change of temperature as a function of dynamic stress for both 3rd and 5th transverse resonance modes of two specimens with fatigue cracks. It is clear that Difference (NETD) of the infrared camera is 20 mK, therefore, temperature changes less than 0.02 K will be considered as noise and were discarded. All specimens tested have the similar frequency dependence individually, however, the absolute response amplitudes vary, which indicates that there are crack related factors, such as crack size, surface roughness, crack orientation, that are not considered in this experiment.

In order to eliminate the unwanted crack related factors and reduce scattering, we assumed that the response has the following pattern:

\[ \Delta T = A \alpha^\alpha f^\beta \]

where \( A \) is crack related parameter, which varies from specimen to specimen, \( \alpha \) and \( \beta \) are two constant parameters that are applicable to all the specimens.

To estimate the value of \( \alpha \), \( \beta \) and possibly \( A \), some statistical models can be used. The most intuitive one is a simple linear model, solving \( \alpha \), \( \beta \) and separate values for \( A \) for each sample. Another approach is to treat \( A \) as a random variable with normal distribution, and use the mixed effect model to estimate the parameters [7]. Estimations of \( \alpha \) and \( \beta \) given by linear model is 1.894±0.022 and 0.712±0.024 respectively, while the same parameters from mixed effect model are 1.894±0.022 and 0.711±0.024 respectively. It can be seen that both models provides very close values of \( \alpha \) and \( \beta \), which is expected because the only difference is the treatment of \( A \).

Viscous-material filled (VMF) synthetic defects were also tested in the experiment. The defects were made by drilling flat-bottom holes and filling with some viscous fluid such as honey. It can be verified that defects close to anti-nodes of flexural resonance
FIGURE 1. Plots of the theoretical and experimental mode shapes. Experimental results were from surface motion scanning using vibrometer. (a) 3rd order flexural mode, (b) 4th order flexural mode and (c) 5th order flexural mode.

FIGURE 2. Temperature increases for two specimens with fatigue cracks as function of dynamic stress at 3rd and 5th flexural resonance modes. Frequencies in (a) are 13.4 KHz and 28.8 KHz for 3rd and 5th modes, frequencies in (b) are 13.7 KHz and 29.5 KHz for 3rd and 5th modes.
generate more heat than defect close to nodes, which is consistent with the known
distribution of dynamic stress. The temperature rises in these synthetic defects were much
higher than in real cracks, thus better signal to noise ratio was obtained.
heat responses for the two modes are distinct from each other, and higher frequency tends
to generate more heat at the same stress level. The Noise Equivalent Temperature
Figure 3 shows the temperature increase of a particular synthetic defect at four different
frequencies/modes. The defect (crack) related parameter $A$
will be the same and thus the
temperature rise should be only a function of dynamic stress and frequency. As expected,
higher frequency provides more IR signal at the same stress level. Repeating the same
statistical analysis described above, estimated values of $\alpha$ and $\beta$
from the both linear model and mixed effect model are 1.940±0.012 and 1.233±0.020 respectively.

CONCLUSIONS

In both fatigue cracks and VMF synthetic defects, higher excitation frequencies
generate more heat at the same dynamic stress level, although the mechanisms are
different for two cases. For fatigue cracks, heat generation is associated with friction
between crack surfaces; while for VMF synthetic defects, heat is generated by viscoelastic
absorption. The stress exponent is approximately 2 (quadratic) in both fatigue cracks and
synthetic defects, while the frequency exponent is approximately 1 (linear). It has to be
stressed here that the values of these parameters also depend on the quantities chosen to
represent the amount of heat or energy generated. In general, heat generation increases
with frequency.

ACKNOWLEDGMENTS

This material is based upon work supported by the National Science Foundation under
Grant No. IIP0334891.

Any opinions, findings, and conclusions or recommendations expressed in this material
are those of the author(s) and do not necessarily reflect the views of the National Science
Foundation.
REFERENCES