Short Communication

Thermosonic Chladni figures for defect-selective imaging

Igor Solodov a,⇑, Daria Derusova b, Markus Rahammer a

a University of Stuttgart, Institute of Polymer Technology (IKT), 70569 Stuttgart, Germany
b National Research Tomsk Polytechnic University, 634028 Tomsk, Russian Federation

Article info
Article history:
Received 17 December 2014
Received in revised form 2 February 2015
Accepted 12 February 2015
Available online 5 March 2015
Keywords:
Ultrasonic heat generation
Thermosonic NDT
Defect-selective imaging

Abstract
Thermosonic patterns produced by resonant vibrations of simulated and realistic defects are experimentally observed and compared with conventional vibration Chladni figures. The patterns are interpreted on the basis of hysteretic damping model that accounts for in-plane polarization component of vibrations. The analysis and simulation results show that thermosonic Chladni figures are the patterns of dissipation of vibration energy determined by a square of the in-plane strain developed in the resonant vibrations. The difference in nodal patterns between the two types of Chladni figures is due to additional extension–compression of the material mainly in near boundary area. The contribution of various order resonance modes in single-frequency imaging is illustrated and their superposition is shown to produce a full-scale thermosonic image of a resonant defect in a wideband excitation mode.

1. Introduction

Initiated by pioneering work Mignogla et al. [1] heat generation by ultrasonic vibrations in solids has become the field of intensive studies and engineering applications in ultrasonic non-destructive testing (NDT). An ultrasound induced excess temperature rise is used in ultrasonic thermography (also called vibrothermography, thermosonics) for imaging of defects in various materials. However, the bottleneck problem of thermosonic applications NDT is the low efficiency of ultrasonic vibration-to-heat conversion, which is usually taken for granted. The solution proposed recently is based on the resonant ultrasonic excitation of a defect area via the concept of Local Defect Resonance (LDR) [2]. The LDR strongly intensifies local defect vibrations and enhances substantially the efficiency of vibro-thermal conversion as well as the sensitivity of thermosonic imaging.

Besides dramatic increase in the local vibration amplitude at the fundamental LDR frequency, the resonant vibration patterns of the defect area manifest the higher-order resonances, which inherit the nodal features of Chladni figures [3]. The Chladni-type resonance vibrations of defects were observed by using scanning laser vibrometry and applied for resonant ultrasonic spectroscopy and imaging of defects [4]. Similar to Chladni experiments with sand, the laser vibrometry is normally sensitive to out-of-plane vibration components and virtually visualizes vibration Chladni patterns.

However, due to internal friction between the elements of defects, their resonant vibrations are accompanied by conversion of ultrasonic energy into heat. Since the internal friction is expected to be related to the in-plane vibration components, instantaneous heat distributions in the resonant area should be, seemingly, different from those observed in experiments with moving particles. It is, therefore, of interest to compare temperature figures produced by resonant vibrations (thermosonic Chladni figures) with conventional vibration (sonic) patterns. In addition, understanding of formation of thermosonic Chladni figures is important for recognition and interpretation of ultrasound induced temperature images of extended defects (e.g. delaminations in composites) in thermovision NDT applications.

An attempt to visualize thermal conversion in resonant ultrasonic vibrations was undertaken back in 1978 [5] by using infrared telethermography apparatus. Due to a low sensitivity of the scanning camera used at that time (0.2 K) the relation between thermal and vibration patterns could not be traced in detail. In this communication, thermosonic Chladni figures are experimentally observed and compared with resonant vibration patterns of simulated and realistic defects. The thermosonic figures are analyzed on the basis of hysteretic damping model related to the in-plane polarization of vibration. The contribution of various order resonance modes in single-frequency imaging is illustrated and their superposition is shown to produce a full-scale thermosonic image of a resonant defect in a wideband excitation mode.

⇑ Corresponding author.
2. Results and discussion

The difference between thermosonic and vibration Chladni figures is clearly seen from Fig. 1 by comparing a fundamental LDR vibration pattern of a circular flat-bottomed hole (FBH) and the ultrasound induced temperature pattern in the same defect. A smooth Gaussian-like LDR vibration profile inside the FBH (Fig. 1, center) generates a strong local heating in the center surrounded by a temperature rise ring along the circumference (Fig. 1, right).

2.1. Theoretical approach

To characterize ultrasonic heat generation in resonant vibrations of FBH we have, first, to determine the in-plane deformation \( \varepsilon_r \), caused by the out-of-plane displacement \( U(r) \) of Chladni vibration patterns and responsible for material internal friction. The extension–compression \( \varepsilon_r \) is zero in the middle plane of the plate and reaches maximal values on its both surfaces [6]:

\[
\varepsilon_r = \frac{d}{2} \left( \frac{\partial^2 U(r)}{\partial r^2} \right),
\]

where \( d \) is the thickness of the plate in the bottom of FBH.

For a fundamental resonance, the radial distribution of \( U(r) \) in a circular FBH (radius \( R \)) with a clamped boundary is given in [7]:

\[
U(r) = \sum_{n=1}^{\infty} a_n (1 - (r/R)^2)^n.
\]

The defect thermal response is caused by a local dissipation of ultrasonic energy due to internal friction, which is described by introducing a complex material elasticity \( E(1 + j\eta) \), where \( \eta \) is the material loss factor. The complex stiffness brings about stress–strain dependence (hysteretic damping model) with an area of the ellipse \( \Delta W = c E \varepsilon_0^2 \) equal to the energy damping in a unit volume of the material per cycle of vibration. The heat energy generated by ultrasonic vibration with frequency \( \omega \) per unit time (heat power) is therefore:
The radial distribution of the in-plane strain $e_r$ is calculated by substituting (2) in (1). The temperature profile generated by LDR vibrations can then be found by squaring the in-plane strain distribution. To this end, for a given vibration amplitude $U(0)$ (measured by laser vibrometry) the absolute values of $e_0$ in (2) are found and then used in calculating $e_r$ in (1). The values obtained are substituted in (3) to determine the heat energy generated in the defect and thus the temperature rise $\Delta T(r)$ in the defect over a certain insonation time $t$:

$$\Delta T(r) = \frac{\omega e_0^2 \eta E t}{2 \rho c_H},$$

(4)

where $E$ is Young's modulus, $\rho$ is the mass density and $c_H$ is the specific heat of the material.

The calculations of the temperature profile for a fundamental LDR in a circular FBH in PMMA carried out from (1)–(4) for the following experimental parameters: $R = 1$ cm; $d = 1$ mm; $t = 10$ s; $U(0) = 8 \times 10^{-7}$ m; $E = 4.8$ GPa; $\eta = 0.02$ are shown in Fig. 2 and compared with the experimental data (LDR frequency 12,480 Hz). Two additional peaks in the temperature profile are caused by “stretching” of the material in the near-boundary area. A very close fit between the calculations and the results of measurements confirm validity of the approach developed.

According to the analysis presented, thermosonic Chladni figures are the patterns of dissipation of vibration energy determined by a square of the in-plane strain developed in the resonant vibrations. This general relation between vibration and thermosonic Chladni figures by means of dissipation can be used for simulation of thermal patterns for various order resonances using FEM approach in Comsol multiphysics (Fig. 3). The FE model uses a body load vibrating at LDR frequencies. The linear elastic material model includes damping via the isotropic loss factor $\eta$ that is also the source for the heat generation by means of ultrasonic power dissipation.

2.2. Experimental

To verify thermosonic Chladni patterns in experiment, temperature images of resonant vibrations of FBH in PMMA were measured by using sensitive IR camera (IRCAM Equus 327 K, NETD $\approx 15–20$ mK) in a wide ultrasonic frequency range (1–200 kHz) to include the higher-order LDR. To enhance signal-to-noise ratio lock-in methodology [8] was applied to obtain phase images of defects shown for a circular FBH in Fig. 4 along with vibration Chladni patterns visualized at the same frequency with scanning laser vibrometry (Polytec PSV 300). Similar historical pictures of Chladni figures from his experiments [3] are also given in Fig. 4 for comparison. A good agreement between the thermosonic...
experiment and the simulation results in Fig. 3 confirms the dissipation mechanism involved in thermal images.

It is instructive noting that the thermosonic Chladni figures of a circular FBH are similar to transverse modes of a cylindrical laser resonator (TEM\(mn\) modes)\(^9\) that points out the generality of resonant phenomena for different types of waves. The same notations are therefore also applied to the thermosonic modes: \(n\) is the number of nodal rings and \(m\) denotes the number of nodal diameters in the images.

Comparison of the thermosonic and vibration patterns in Fig. 4 shows that the areas of maxima of out-of-plane displacements predictably provide maximal thermal response. However, in accord with the methodology given above, the quadratic in-plane strain produces extra nodal and anti-nodal rings near the boundary, so that the \((n, m)\) vibration Chladni mode generates the \((n + 1, m)\) thermosonic mode (Fig. 4).

It is worthwhile noting that the additional anti-nodal rings, which are due to extension–compression of the periphery, provide a strong heating and a clear image of the boundary of the defect. This feature is beneficial for the quality of thermosonic imaging: unlike laser vibrometry even the low-order resonant thermosonic patterns visualize the contours of defects and thus applicable for recognizing a real defect size. To image an entire defect area various order \((n, m)\) thermosonic images can apparently be superimposed. To this end, wideband ultrasonic signal (1–200 kHz) was used to insonify a circular FBH with fundamental LDR of 6640 Hz to excite multiple resonances. The image shown in Fig. 5 confirms
the applicability of this approach to full-scale defect-selective imaging.

The “edge effect” of extra heating is also traced in thermosonic Chladni figures simulated for rectangular FBH defects in Fig. 6 and compared with corresponding vibration patterns. Since the additional anti-nodal temperature lines are due to in-plane stretching of the boundary they predictably reproduce the square profile for various order resonances as well.

This makes thermosonic images substantially distinct from their vibration counterparts particularly at low-order resonances. The difference is readily observed experimentally for a square FBH at fundamental LDR frequency 8940 Hz (Fig. 7): a real size and shape of the defect becomes evident only in the thermosonic image. At higher driving amplitude, the effect manifests even for non-resonant vibration modes as seen from Fig. 8 for a square (20 × 20 mm²) delamination in carbon fiber reinforced plastic (CFRP) (LDR frequency 68 kHz) excited in the frequency range 15–25 kHz. The impact of wideband excitation on resonant imaging of defects is also illustrated in Fig. 9 for a square inset (27 × 27 mm²) in CFRP plate. The excitation of the defect with fundamental LDR of 8890 Hz by using a periodic sweep mode (1–200 kHz bandwidth) results in a superposition of various order resonant patterns (both thermosonic and vibration) and reproduces an entire shape of the defect.

3. Conclusion

Thermosonic analogs of famous Chladni figures manifest themselves in NDT and imaging of resonant defects in ultrasonic thermography. They are caused by the in-plane strain components of vibrations and produce nodal line distributions distinct from conventional vibration counterparts. Unlike laser vibrometry even the low-order resonant thermosonic patterns visualize the contours of defects and thus applicable for recognizing a real defect size. To develop a full-scale thermosonic image of a resonant defect the wideband excitation mode which covers multiple-order resonances has to be used.

Acknowledgements

One of the authors (I.S.) acknowledges support of this study in the framework of ALAMSA project funded from the European Union’s Seventh Framework Programme for research, technological development and demonstration under grant agreement No. 314768. The authors are also grateful to Professor Gerd Busse (University of Stuttgart) for fruitful discussions.

References

[1] R.B. Mignogna, R.E. Green Jr, J.C. Duke Jr, E.G. Henneke II, K.L. Reifsnider, Thermographic investigation of high-power ultrasonic heating in materials, Ultrasonics 19 (1981) 159–163.
[2] I. Solodov, J. Bai, S. Bekgulyan, G. Busse, A local defect resonance to enhance acoustic wave-defect interaction in ultrasonic nondestructive testing, Appl. Phys. Lett. 99 (2011) 211911.
[3] E.F.F. Chladni, Entdeckungen über die Theorie des Klanges, Beichmanns & Reich, 1787.
[4] I. Solodov, J. Bai, G. Busse, Resonant ultrasonic spectroscopy of defects: case study of flat-bottomed holes, J. Appl. Phys. 113 (2013) 223512.
[5] J.-L. Garnier, C. Gazanhes, Visualization of ultrasonic vibrations in piezoelectric ceramics using telethermography, IEEE Trans. Son. Ultrason. 25 (1978) 68–71.
[6] L.D. Landau, E.M. Lifshitz, Theory of Elasticity, Pergamon Press, 1959.
[7] S.P. Timoshenko, Vibration Problems in Engineering, D. Van Nosstrand Company, 1956.
[8] J. Rantala, D. Wu, G. Busse, Amplitude modulated lock-In vibrothermography for NDE of polymers and composites, Res. Nondestruct. Test. 7 (1996) 215–228.
[9] A.E. Siegman, Lasers, University Science Books, Mill Valley, CA, 1986.