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Characterization of vertical buried defects using lock-in vibrothermography: I. Direct problem

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Abstract
The ability of lock-in vibrothermography to distinguish between different sizes, shapes and locations of vertical kissing defects, such as cracks or corrosion, is analyzed in this work both theoretically and experimentally. We have computed the oscillating, AC, surface temperature of samples containing inner modulated heat sources, representing the defect, and analyzed the sensitivity of this oscillating temperature to the defect geometric parameters. Moreover, we have prepared samples with calibrated vertical defects. Vibrothermographic data are usually recorded under non-steady conditions (i.e. while the surface temperature is still rising). As this transient temperature rise has a non-negligible component at the excitation frequency, the measured AC temperature is strongly distorted. By subtracting the Fourier component of the transient temperature rise from vibrothermographic data, we obtain the pure AC temperature (amplitude and phase) in very good agreement with the theoretical predictions.

Keywords: vibrothermography, ultrasonic thermography, nondestructive evaluation, infrared thermography

1. Introduction
Infrared thermography with ultrasound excitation known as vibrothermography, ultrasonic thermography or sonic infrared has been receiving an increasing amount of attention in the last decade because of its ability to detect defects such as cracks, delaminations, corrosion or disbonds in all kind of materials: metals, polymers, ceramics and composites [1–6]. In these experiments, the sample is excited by launching an ultrasonic wave into the material. In metals, where the viscoelastic effect is almost negligible, mechanical energy is converted into heat at the position of the defects, due to friction between its faces and/or stress concentration in the surroundings. This way, in the presence of ultrasound, the defect ‘turns’ into a heat source on a dark background.

The activity in the field of vibrothermography has covered different aspects aimed at understanding the mechanisms of signal generation and the influence of the experimental configuration on the detected signal with the ultimate goal of being widely deployed in industry. The primary question discussed in the literature is the nature of the main mechanisms of heat generation at the defects. Although friction between the defect surfaces has been widely accepted as the main mechanism for heat generation [7, 8], it has also been stated that heat dissipation takes place because of the elasto-plastic area around the crack tip [9]. Recently, experimental evidence of heat generation in defects due to three different mechanisms (friction, plasticity and viscoelasticity) has been demonstrated [10]. Concerning signal generation by friction, several authors have demonstrated the relation between the propagation of the acoustic wave, giving rise to a relative motion between the defect faces, and the heat generated there comparing finite element calculations and experiments [7, 11]. Nonlinear and defect resonance effects leading to the generation of new ultrasound frequencies that enhance detectability have also been studied [12–14]. Moreover,
lock-in experiments, the consequences of generating standing waves in the sample have also been analyzed by several authors, demonstrating lack of detectability when the defect sits at the location of a node [15–18]. In these experiments, frequency modulation in addition to amplitude modulation has been demonstrated to reduce the intensity of standing wave patterns and enhance defect detection [15–17]. Moreover, the existence of ultrasound frequencies providing maximum acoustic wave-defect interaction has been demonstrated by several authors [19, 20].

The development of vibrothermography has been burdened by reproducibility issues, preventing a wide acceptance of the technique. Recently, the modification of the defect surface asperities after several vibration cycles has been identified as one of the mechanisms contributing to the lack of repeatability [21]. As a conclusion of the study, authors propose a rule of thumb consisting of applying vibrational stresses below 20% of the material’s endurance limit to reduce tribological damage and improve reproducibility. Moreover, recent studies on the probability of detection of cracks as a function of the crack length have resulted in similar estimates for three different crack sites of particular specimens excited at natural resonances [22].

Another relevant question for the spreading of the technique is its ability not only to detect but also to quantitatively characterize defects. Correlation between crack heating, local vibrational stress and crack length under longitudinal excitation of the crack has been demonstrated by different laboratories obtaining similar results [23]. The ability of vibrothermography for crack characterization has been shown by modeling the thermosonic signal generated by surface breaking and submerged cracks in burst experiments [24]. Our work is aimed at showing the full potential of vibrothermography as a nondestructive evaluation technique, to characterize (determine dimensions and location of) defects.

Among all the physical processes involved in the experiments (the coupling between the vibrator and the sample, the propagation of ultrasounds, the mechanisms by which heat is produced at the defect and the diffusion of this thermal energy within the sample) we focus on the last steps. We assume that heat is generated at the defect and study the propagation of this thermal energy to the sample surface. We calculate the amplitude and phase lag of the surface temperature are measured by means of an infrared video camera. We calculate the amplitude and phase of the surface temperature distribution corresponding to a given internal heat source (size and depth) and compare these predictions with the results of vibrothermographic data taken in samples with calibrated vertical defects. The experimental results show that the transient temperature rise of the sample strongly affects the amplitude and phase of the measured thermograms. By subtracting the Fourier component of this transient temperature rise, we have obtained very good agreement between theory and experiments, allowing us to avoid the need of waiting for the steady state to be reached. In part II, we invert these experimental results to reconstruct the size and shape of the calibrated heat sources, showing the capability of the technique to retrieve the geometry of inner heat sources.

2. Theory and simulations

In this section we calculate the surface temperature distribution generated by a subsurface vertical heat source, representing the defect, located in a sample of thickness e, infinite in x and y directions (see figure 1(a)). The intensity of the heat source is modulated at frequency f.

![Heat source plane](image)

Figure 1. (a) Geometry of a vertical buried defect of arbitrary shape. Cross-sections of the three defect shapes analyzed in the text: (b) rectangular, (c) semicircular upward and (d) semicircular downward.

We start by the calculation of the temperature generated by a point-like heat source, located at \( \vec{r}_0(x_0, y_0, z_0) \) in an infinite medium, whose intensity is modulated at frequency f. The AC temperature at any point of the sample \( \vec{r}(x, y, z) \) is the normal solution of the Helmholtz equation [25],

\[
T(x, y, z, t) = \frac{P}{8\pi K} e^{-\frac{q}{\mathcal{D}}} \sqrt{\frac{\pi f}{\mathcal{D}}} \frac{\mathcal{D}}{\mathcal{D}^2} e^{i\omega t},
\]

where \( P \) is the maximum emitted power, \( q = \sqrt{2\pi f/\mathcal{D}} \) is the thermal wave vector, \( \mathcal{D} \) is the thermal diffusivity and \( K \) is the thermal conductivity. Equation (1) represents a damped spherical wave, and the square root represents the distance between the heat source and the position where the temperature is calculated. If we now consider an extended heat source, spread over an area \( \Omega \), contained in the Y-Z plane, the temperature at any point of the infinite medium can be calculated by adding the contributions of point-like heat sources covering area \( \Omega \). Then, the position-dependent part of the AC temperature can be computed as

\[
T(x, y, z) = \int_{\Omega} Q(0, y_0, z_0) \frac{e^{-q\sqrt{(x-x_0)^2+(y-y_0)^2+(z-z_0)^2}}}{\sqrt{\alpha^2 + (y-y_0)^2 + (z-z_0)^2}} dy_0 dz_0.
\]

where \( Q \) represents the position dependent power density (flux) emitted over area \( \Omega \).
Now we have to take into account the actual thickness, \(e\), of the sample. If we assume adiabatic conditions at the sample surfaces, the finite thickness of the sample can be taken into account by applying the images method, in which the effect of the surface boundary is equivalent to having successive reflection images of the heat source at the sample surfaces. In this way, the position-dependent part of the temperature is given by

\[
T(x, y, z) = \int_{\Omega + \Omega' + \Omega'' + \Omega''' + \ldots} \frac{Q(0, y_0, z_0)}{8\pi K} e^{-\sqrt{\frac{x^2}{\Omega^2} + (y - y_0)^2 + (z - z_0)^2}} \, dy_0 \, dz_0,
\]

where \(\Omega'\) is the reflection of \(\Omega\) at the front surface of the sample \((z = 0)\), \(\Omega''\) is the reflection of \(\Omega'\) at the rear surface of the sample \((z = -e)\), and \(\Omega'''\) is the reflection of \(\Omega\) twice, first at the front surface and then at the rear surface, and so forth.

In the experiments performed in this work, the sample is made of AISI 304 stainless steel \((D = 4 \text{ mm}^2 \text{ s}^{-1})\), the sample thickness is \(e = 1.5 \text{ cm}\) and the minimum modulation frequency of the ultrasound amplitude is 0.05 Hz. Under these conditions we have checked that the rear \((z = -e)\) surface does not affect the temperature distribution at the front surface, where data are taken \((z = 0)\). Accordingly, all the terms in equation (3) vanish except the first two. Moreover, as metallic samples are opaque to IR radiation only the surface temperature is recorded by the IR camera, which is written as

\[
T(x, y, 0) = \int_{\Omega} \frac{Q(0, y_0, z_0)}{8\pi K} e^{-\sqrt{\frac{x^2}{\Omega^2} + (y - y_0)^2 + z_0^2}} \, dy_0 \, dz_0.
\]

Note that this expression is equivalent to considering a thermally semi-infinite sample. Moreover, it is valid for heterogeneous inner heat sources (position varying intensity) of any shape \(\Omega\). However, in the following only homogeneous heat sources (i.e. constant \(Q\) over the heat source area \(\Omega\)) will be analyzed. We will consider heat sources of two different geometries: a rectangle and a semicircle.

### 2.1. Rectangular heat source

We first study the case of a rectangular heat source, of height \(h\) and width \(w\), submerged at depth \(d\). For this geometry, depicted in figure 1(b), equation (4) is written as

\[
T(x, y, 0) = \int_{-w/2}^{w/2} \int_{-d}^{d} \frac{Q}{4\pi K} e^{-\sqrt{\frac{x^2}{w^2} + (y - y_0)^2 + z_0^2}} \, dy_0 \, dz_0.
\]

We use this first case to analyze the influence of the geometrical parameters of the heat source on the surface temperature. To do so, we have computed the phase, \(\Psi\), and the natural logarithm of the amplitude, \(\ln(|T|)\), of the surface temperature \((z = 0)\) for different values of the size parameters \((w\) and \(h)\) and different depths \((d)\) of the heat source, at various modulation frequencies. We have taken a standard square of 1 mm side \((w = h = 1 \text{ mm})\) and checked the influence of variations of 50% and 200% in these parameters. For the sake of clarity, instead of comparing amplitude and phase surface maps we have compared two key profiles: \(x\)-profile, perpendicular to the heat source along the \(x\)-axis, and \(y\)-profile, parallel to the heat source along the \(y\)-axis. All calculations are performed for AISI-304 stainless steel \((D = 4 \text{ mm}^2 \text{ s}^{-1})\) and the results are shown at two frequencies, \(f = 0.05\) and 6.4 Hz, representative of extreme frequencies used in the experiments. In all the simulations, the surface temperature amplitudes have been normalized to the value at position \((0, 0, 0)\). Moreover, they have been shifted along the vertical axis to better distinguish between amplitudes and phases.

In figure 2 we show the effect of modifying the width \((w = 0.5, 1\) and 2 mm\) of a \(h = 1\) mm tall heat source reaching the sample surface \((d = 0)\) on the surface temperature. It can be seen that both \(x\)-profiles and \(y\)-profiles are sensitive to width variations: on the one hand, in \(y\)-profiles the width of the flat center follows the width of the defect. Moreover, differences in defect width also affect \(x\)-profiles by changing the slope of the branches of amplitude and phase.

The effect of modifying the height \((h = 0.5, 1\) and 2 mm\) of a \(w = 1\) mm wide heat source reaching the surface \((d = 0)\) is shown in figure 3. As can be observed, the deeper the defect, the wider both \(x\)-profiles and \(y\)-profiles. Anyway, the differences are bigger in amplitude than in phase. Regarding the amplitude, differences in the height of the heat source are better distinguishable at low frequencies. This is because at high frequency, due to the damped character of thermal waves, the additional effect of heat sources located at increasingly deeper positions barely affects the surface temperature distribution.

Finally, the effect of burying our standard square \((1 \text{ mm} \times 1 \text{ mm})\) heat source at different depths \((d = 0, 0.25, 0.5\) and 1 mm\) is shown in figure 4. The simulations show that deep heat sources give rise to round instead of sharp profiles close to the center. At large distances, all phase values converge.

Moreover, deeper heat sources produce wider amplitude profiles. It is worth noting that, contrary to what happens for different heights, the effect of different depths is better distinguishable at ‘high’ frequencies. As high frequencies provide a higher spatial resolution, differences in surface temperature with the depth of the heat source are more pronounced at these frequencies.

In the case the heat source is buried inside the material \((d > 0)\) the results shown in figures 2 and 3 retain the same features but the profiles are closer to each other, meaning that the deeper the heat source, the more difficult it is to distinguish between different sizes.

### 2.2. Semicircular heat source

Now we consider a semicircular heat source, of radius \(R\), buried at a depth \(d\) \((\text{depth measured at the shallowest side of the heat source})\). We use this example to show the ability of vibrothermography to distinguish between different shapes of heat sources having similar dimensions. We consider two configurations, with the flat side either upward or downward, as depicted in figures 1(c) and (d), respectively. In the case of
the flat side being upward, equation (4) reduces to

\[
T(x, y, 0) = \int_0^R \int_0^{2\pi} \frac{Q}{4\pi K} e^{-q\sqrt{x^2 + (y - r_0 \cos \phi_0)^2 + (d + r_0 \sin \phi_0)^2}/r_0} \, dr_0 \, d\phi_0,
\]

while if the flat side is downwards, equation (4) is written

\[
T(x, y, 0) = \int_0^R \int_0^{2\pi} \frac{Q}{4\pi K} e^{-q\sqrt{x^2 + (y - r_0 \cos \phi_0)^2 + (R + d + r_0 \sin \phi_0)^2}/r_0} \, dr_0 \, d\phi_0.
\]

In figure 2 we compare the surface temperature along the x-profile and the y-profile for a semicircular heat source of radius \( R = 1 \) mm and a rectangular heat source of dimensions \( R \times 2R \), both reaching the sample surface \( (d = 0) \). Calculations are performed for AISI-304 at an intermediate frequency of \( f = 0.8 \) Hz. Figure 5(a) shows the comparison when the flat side of the semicircular heat source is downward. As can be seen, differences in both x- and y-profiles allow us to distinguish between them. However, when the flat side is upward (see figure 5(b)) the buried structure of the heat source cannot be distinguished.

All the previous results show that information on the dimensions and location of the heat source affects different aspects of the surface temperature: depending on the parameter to be determined high or low frequencies may be better suited, amplitude or phase may display more information, the temperature distribution closer or further away from the heat source may better reveal certain details. This indicates that, in order to characterize a given heat source, full amplitude and phase surface thermograms need to be recorded, in the widest possible modulation frequency range, in order to gather as much information as possible. Moreover, features on the shape of the heat source are only distinguishable if they are located close to the surface, but not if on the deeper side of the defect.

3. Experiments and discussion

In order to test the predictions of the theory presented above, we have prepared samples with calibrated internal heat sources.
representing the defect. To do so, we have built two AISI 304 stainless steel parts with a common flat surface. We have placed a thin (38 μm) Cu foil between these flat surfaces and pressed them with screws. Figure 6 shows a diagram of the samples.

When the ultrasound is launched into the sample, friction takes place between the Cu foil and the steel planes. In order to guarantee that friction only occurs at the location of the foil and not between the steel planes (i.e. we have a calibrated heat source), two additional foils are placed at the back side of the planes, far enough from the measuring surface so that the thermal waves generated there do not affect the data. The dimensions of the foils are measured by means of an optical stereoscope.

Ultrasound excitation has been performed with UTvis equipment from Edevis. Ultrasound frequencies can be varied from 15 to 25 kHz, at a maximum power of 4 kW (at 20 kHz). Excitation can be performed either at a fixed ultrasound frequency or modulating the ultrasound frequency. In our experiments we excite the sample at a fixed, optimum ultrasound frequency, typically around 22 kHz, that we determine by performing frequency sweeps at a constant ultrasound amplitude [17, 20]. Excitation powers typically range between 150 and 250 W. Amplitude modulation of the ultrasound is carried out by means of function generators and in our experiments modulation frequencies range from 0.05 Hz up to 12.8 Hz.

The thermal energy generated at the foils diffuses into the material and reaches the sample surface. In order to enhance IR emission from the sample, black paint was applied to its surface with the two halves joined with the screws, before introducing Cu foils. The infrared radiation emitted from the surface is captured by an infrared video camera (JADE J550M from Cedip), working in the 3.6–5 μm range. The camera is provided with a 50 mm focal length lens. Each pixel in the detector averages the temperature of a 135 μm square in the sample, at the minimum working distance. We capture about 30 frames per cycle and average the signal over 10–100 periods (more periods at high frequency) in order to enhance the signal-to-noise ratio.

In figure 7 we show the experimental amplitude and phase thermograms obtained at 0.1 and 6.4 Hz for a Cu foil (heat source) with dimensions: $h = 2.3$ mm, $w = 1.4$ mm, buried at a
depth of $d = 95 \mu m$. Note that gray scales are not comparable. When analyzing the results far away from the defect, two different types of behavior are observed depending on the modulation frequency. At 6.4 Hz the amplitude is very small and the phase is random, in agreement with the fact that far away from the defect the thermal wave vanishes. However, at 0.1 Hz there is a remaining amplitude and a rather stable phase.

This result can be better appreciated if we draw $x$-profiles at both frequencies (see dots in figure 8). This remaining thermal signal in regions where the thermal wave has already vanished is related to the fact that vibrothermographic data are recorded in the transient state, i.e. while the temperature of the sample is still increasing all over the sample volume. This continuously rising temperature has a Fourier component at the excitation frequency that adds to the thermal signal generated at the heat source. As this transient temperature rises slowly, its Fourier component is larger at low frequencies, as illustrated in figure 8.

In order to obtain the pure oscillating contribution to the surface temperature, we have subtracted the Fourier component of the transient temperature rise of the sample, obtained as the signal far away from the heat source, where the thermal wave is already damped. As a first approximation, we assume that the Fourier component is the same all along the profile and subtract its value from the raw experimental temperature data in all pixels in the profile. This simplified approach relies on two assumptions: on the one hand, we assume perfect optical behavior of the IR camera optics, i.e. we leave aside the fact that the IR radiation collected by pixels aimed at imaging a certain region of the sample might be coming from other regions. This effect is caused by the imperfect transfer function of the optics. On the other hand, the assumption of uniform contribution of the transient component is not rigorously true. The heat source acts as a continuous source on top of which modulation occurs. The temperature rise due to the continuous heat deposition is a function of the distance to the heating region. Despite these limitations, the method is fast and easy to implement, and gives rather satisfactory results in terms of coincidence between experiments and simulations, with slight discrepancies at low frequencies. As an example, in figure 8 we show raw data with dots, the processed data with crosses and the theoretical prediction from equation (5) with solid lines. As can be seen,
raw data strongly differ from the simulations but, after correction, data follow very well the prediction of the theory.

We have performed vibrothermographic measurements for the same sample in steady state, i.e., when the temperature of the sample has reached equilibrium. These data are very similar to those obtained after subtracting the Fourier component in non-steady measurements, confirming that the origin of the additional signal is the increasing temperature of the sample. Anyway, reaching the steady state is rather time consuming and, in addition, the equilibrium sample temperature might be significantly above ambient temperature (typically between 10 and 30 °C above ambient for the ultrasound amplitudes used in our experiments). For these reasons, we decided to take data in the transient state and perform the post-processing described above to remove the transient contribution from the thermograms obtained at frequencies below 1.6 Hz. At higher modulation frequencies, raw data agree with the predictions of the model very satisfactorily, as illustrated in figures 8(a), 9 and 10.

In figure 9, we show ln(|T|) and Ψ of the surface temperature x-profiles for the same AISI-304 sample as before, but with a rectangular Cu foil with the following dimensions: width $w = 2.34$ mm, height $h = 1.39$ mm, buried at depth...
Figure 7. Amplitude (a) and phase (b) thermograms obtained at 0.1 Hz and 6.4 Hz with a calibrated heat source of width \( w = 1.4 \) mm, height \( h = 2.3 \) mm and buried at a depth of \( d = 95 \) \( \mu \)m.

Figure 8. Experimental \( \ln(|T|) \) and \( \Psi \) of the surface temperature \( x \)-profiles for an AISI-304 sample with a rectangular Cu foil simulating a vertical heat source. The Cu foil has width \( w = 1.40 \) mm, height \( h = 2.30 \) mm and is buried at depth \( d = 95 \) \( \mu \)m. Dots stand for raw data, crosses correspond to processed data and solid lines are the predictions of the theory. Results for two frequencies are shown: (a) \( f = 6.4 \) Hz and (b) 0.1 Hz.
Figure 9. The same as in figure 8, but for a rectangular Cu foil of width \( w = 2.34 \) mm, height \( h = 1.39 \) mm and depth \( d = 0 \) \( \mu m \). Experimental data are shown with crosses, processed for 0.1 Hz and raw for 6.4 Hz, for both \( x \)-profiles and \( y \)-profiles.

Figure 10. The same as in figure 9, but for an isosceles triangular Cu foil of base \( b = 1.76 \) mm, height \( h = 1.72 \) mm and depth \( d = 420 \) \( \mu m \).
d = 0 μm. Crosses represent experimental data: processed for 0.1 Hz (i.e. after subtraction of the Fourier component of the transient temperature rise) and raw for 6.4 Hz. The reason for discrete values of amplitude data at 6.4 Hz is an unsuitable choice of the number of digits of temperature in the camera. The solid lines are the predictions of the theory using equation (5), which fit the experimental data very well.

Figure 10 is the same as figure 9, but the Cu foil has an isosceles triangular shape with the non-equal angle pointing downward. The dimensions of the isosceles triangle are as follows: base b = 1.76 mm, height h = 1.72 mm, buried at depth d = 420 μm. Crosses represent experimental data. The solid lines are the predictions of the theory using equation (4) with the appropriate boundaries of the integral. As can be seen, the theoretical prediction fits the experimental data very well. The asymmetry of experimental phase data appearing at 0.1 Hz is due to an additional low amplitude periodic heating occurring because of vibration of one of the screws that started when taking low frequency data.

As far as we know, there is no way to perform normalization in vibrothermographic data in order to remove the frequency dependence of the equipment. Owing to lack of normalization, experimental values of the surface temperature phase do not follow the expected behavior with modulation frequency. For this reason, in figures 8–10 experimental phase profiles have been shifted along the vertical axis, by the right amount for each modulation frequency, to match the theoretical profiles.

For all three geometries of the heat sources corresponding to data shown in figures 8–10 (two rectangles and one triangle), we have taken data at various modulation frequencies: 0.05, 0.1, 0.2, 0.4, 0.8, 1.6, 3.2, 6.4 and 12.8 Hz. In all cases, the agreement between theory and experiments is quite good at medium and high frequencies, but some discrepancies are observed at low frequencies: 0.1 and, particularly, 0.05 Hz. There are two possible reasons for these discrepancies: on the one hand, heat losses might be non-negligible at these low frequencies. On the other hand, as mentioned in the previous section, our approach to remove the transient temperature rise, in which we consider the same contribution of the slow transient heating along profiles perpendicular to the heat source plane, is only an approximation. At low frequency, where the transient contribution increases, the approach might no longer be reasonable. Some authors have addressed this problem by adjusting, for each pixel, the measured temperature variations to a model where an oscillating function is added to a linear function, representing the dissipation effect [19]. Analyzing the effect of heat losses and improving the treatment of the transient heating will be the subject of future work.

4. Summary and conclusions

We have calculated the surface temperature distribution generated by modulated inner vertical heat sources representing defects excited in lock-in vibrothermographic experiments. We have shown the effect of changing the dimensions and location of rectangular and semicircular defects on the surface temperature distribution. Note that equation (3) is also valid for heterogeneous heat sources (with position-varying intensity) of any shape (triangular, elliptical, etc). Moreover, all the calculations performed in section 2 can be easily extended to slanted heat sources making any arbitrary angle with respect to the sample surface.

In experiments performed on samples with calibrated internal heat sources, we have found that vibrothermographic data taken without waiting for the stationary state are strongly affected by the Fourier component of the transient temperature, especially at low modulation frequencies. Performing post-processing to remove the Fourier component of the transient gives very good results without needing to wait for the stationary state, which is time consuming and significantly increases the sample temperature. Experimental surface temperature data obtained under modulated ultrasound excitation of samples with calibrated internal heat sources validate the predictions of the model. In part II, the ill-posed inverse problem consisting of retrieving the geometry and location of heat sources from surface temperature data obtained under modulated ultrasound excitation will be addressed. Experimental data presented in this paper will be inverted to obtain the size and location of the heat sources that produced them.

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