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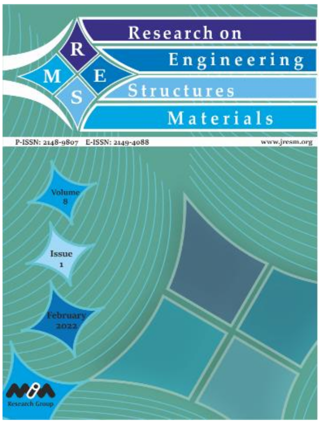

# Recent developments in vibrothermography

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*Review Article*

# Recent developments in vibrothermography

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**Abstract**

Due to the sensitivity of fluorescent penetrant inspection to surface roughness of the inspected material, researchers have been investigating alternative inspection methods. Vibrothermography is one of the contactless non-destructive testing methods in which vibration pulses with high frequencies (typically 20-40 kHz) are used in a part for a short period of time to produce thermal gradient at the defect. In this technique, thermographic or infra-red cameras are used for radiation detection due to thermal gradient in the range of 0.9-14 µm electromagnetic spectrum. This paper focuses on the recent developments in vibrothermography. It covers basics, history, equipments used, types, materials, probability of detection, principle of heat generation mechanism and factors that affect detectability in vibrothermography.

## 1. Introduction

Inspection is one of the main steps in quality control of manufactured parts. Although there are different inspection methods used in different industries, liquid / fluorescent penetrant inspection (FPI) method has found wide industrial application. The main disadvantage of FPI is its need for a very smooth examination surface. Therefore, surface roughness of the examined parts should be lowered by machining, polishing or similar techniques before FPI [1]. Due to this disadvantage, researchers have investigated different alternatives for FPI. One of the alternatives for FPI is infra-red (IR) thermography which is less affected by surface roughness [2]. IR thermography depends on thermal properties of the material and thermal gradients occurred in the inspected part rather than material geometrical parameters which makes it a good inspection alternative to FPI [3].

When an object is heated, it radiates electromagnetic energy. This energy depends on object's temperature. When temperature sensors are used, these sensors collect the energy and make a relation between the intensity of the gathered radiation and object's temperature [4]. Temperature distribution of the surface exposed to a thermal gradient can be recorded by an IR camera [5]. If a material with a crack in the surface and/or sub surface is heated, the thermal gradient over the crack will be different from the surrounding area. This thermal gradient difference can be used to detect and quantify the related crack [6]. Based on this philosophy, IR thermography is a contactless non-destructive testing method for determining the temperature response of a material by converting the radiation that is given off by the surface as it is heated up into an electrical signal through the use of specialized sensors that convert infrared radiation into electrical signals [7].

In electromagnetic spectrum, the infrared spectrum covers 0.74-1000 µm wavelength range. The most widely used wavelength ranges in infrared thermography applications are near IR (NIR) (0.74–1 µm), short-wave IR (SWIR) (1–3 µm), mid-wave IR (MWIR) (3–5

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μm) and long-wave IR (LWIR) (8–14 μm). MWIR and LWIR are widely used for detection of sub-surface defects in non-destructive testing applications [8].

The basis of IR thermography is thermal rays whose existence was believed to be proposed by Titus Lucretius Carus (99-55 BCE), but the first person officially discovered the IR radiation in 19th century is Sir William Herschel who first called it “invisible light” and later “infrared” [9]. Then in 20th century, German physicist Max Planck (Planck’s law) precisely described blackbody radiation. Later, Albert Einstein suggested that photons with separate energies are the basis of an electromagnetic wave, such as light [10]. In 1947, transistor was discovered and after this discovery, the first cryogenic cooled IR detectors emerged. In 1965, first commercial IR cameras were discovered to detect scene images which used a single detector mounted to an optical-mechanical scanning mechanism. From 1970s to 1990s, different IR cameras with more and more resolution have started to be seen commercially (nowadays largest arrays are 2048 × 2048) [11]. Due to the unavailability of IR cameras with high temperature resolution until 1990s, pioneering works lacked continuity but with the development of affordable IR cameras with high temperature resolutions (between 20 to 30 mK range) in the late of twentieth century, IR thermography started to be used widely in different industries [12].

IR thermography needs an external stimulation to produce thermal gradient in the material. This stimulation can be heat lamps, eddy current or mechanical excitation. Based on stimulation types, IR thermography can be categorized mainly as lock-in thermography, pulsed thermography, eddy current thermography and vibrothermography (Fig. 1) [13].

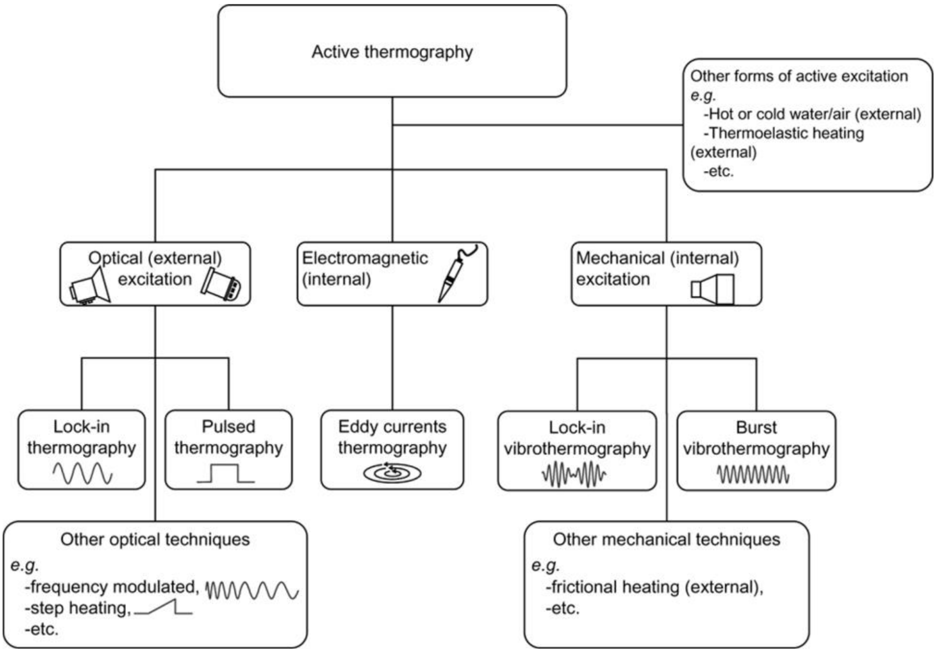

Fig. 1 Active thermography methods [13]

## 2. Basics and History of Vibrothermography

Vibrothermography is a type of IR thermography methods in which ultrasound excitations are used to produce thermal gradient in the material (Fig. 2) [14]. Thermosonics, ultrasonic infrared thermography, sonic IR, acoustic thermography, vibro IR, elastic-wave-activated thermography or thermal vibration method are some of the similar names given to vibrothermography in scientific literature [15]. Vibrothermography is based on the idea of applying a vibration pulse with a high frequency of typically 20-40 kHz to a material for a very limited time of less than one second and with the help of produced thermal gradient at the crack/defect area, using an IR camera to produce images of changes in heating and cooling process [16]. In general, vibrothermography has mainly three main steps; vibration, heat generation and heat detection. First of all, vibration pulse must be applied to the part with the help of a vibration source to interact with any existing defects in inspected specimen. Next, thermal gradient is generated at the defect area due to different mechanisms. Then, this thermal gradient will radiate away from the defect region via conduction and be detected by an IR camera [17].

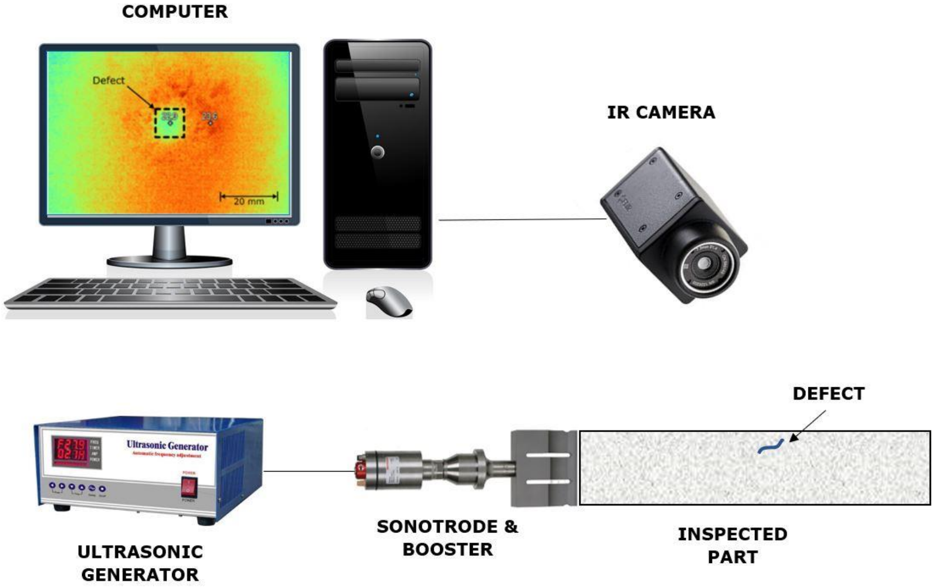

Fig. 2 Vibrothermography with ultrasonic thermal excitation

When a surface and /or a subsurface crack are excited by a nearly 20 kHz vibration pulse, it becomes a thermal source, because of frictional dissipation at the surfaces of the crack [18]. Thomas stated that this thermal source reveals a crack's presence on a time scale much less than a second. He also suggested that only the crack (not saw-cut) heats up significantly in the presence of the vibration excitation [19]. On the contrary to IR thermography, where very narrow cracks may not be detected due to low thermal gradient they produce when subjected to heat, vibrothermography is based on the idea of relative motion of crack faces when sample is excited with ultrasounds. This relative motion produces heat which spreads out in the material and finally reaches surface of the inspected part. IR camera detects this surface temperature elevation revealing the presence of the crack [20]. As Renshaw et al. stated, since frictional rubbing, one of the heat generation mechanisms in vibrothermography, is not affected by crack openings for an effective inspection, vibrothermography has greater reliability with detection of tighter cracks than other non-destructive testing methods [21].

In 1970's Henneke et al. used vibrothermography in composite materials and observed and measured large temperature variations around delaminations. He attributed this thermal gradient to generated heat at delaminations and low thermal conductivities of polymer-based materials [22]. This was the first usage of vibrothermography in scientific literature, but the details of mechanics of vibrothermography was given by Reifsnider et al. in 1980 [23]. In 1981, Mignogna et al. used vibrothermography technique to detect cracks in steel, brass, copper and aluminum parts. They concluded that if there were no large defects in the material, heat was observed to flow uniformly through the material, but if there were natural and artificial defects, such as grain boundaries, fatigue cracks and saw cuts, then heat gradient was observed at the sites of these defect regions [24]. Lock-in vibrothermography where response of a material was analyzed with respect to the modulation frequency was proposed in 90s [25]. Then later, in 21st century, ultrasound burst phase thermography [26] and ultrasound frequency modulated thermography [27] were proposed.

Being a very effective technique with simple and robust test setup and short measurement time, vibrothermography requires only simple image processing which makes it easy to implement in various applications [28]. It finds its usage in different industries and applications as non-destructive defect detection; aircraft structure wings, automobile engines, biomedical devices etc. [29]. Zweschper et al. stated that vibrothermography can detect areas of cracks in rows of rivets, hidden corrosion, disbonds, delaminations and impacts in aerospace structures [30]. DiMambro et al. used vibrothermography and detected several cracks in a Boeing 767-wheel half, bolt, brake key and brake manifold and in second and fourth stage turbine blades from a Pratt and Whitney JT-8D aircraft engine [31]. Zalameda et al. used vibrothermography method in helicopter blades and their study successfully revealed core damages in sandwich honeycomb structures [32]. Guo and Ruhge used vibrothermography in service-retired gas turbine blades to inspect low-cycle fatigue cracks. They stated that vibrothermography favors FPI and visual non-destructive testing in terms of defect detection [33]. Szwedo et al. applied vibrothermography to fuselage panels and mating parts of a jet fighter aircraft successfully [34]. Apart from aviation industry, vibrothermography has been applied to bonded joints in modern automobiles to detect defects including entrapped air, kissing bonds, poor adhesion and non-cured or missing adhesive [35], to historical and archaeological discoveries for surface crack and defect detection [36] and to sports equipment for detection of mechanical performance of tennis racket strings [37, 38].

## 3. Vibrothermography Equipments

Generally, a vibrothermography set up consists of a transducer system, specimen, IR camera and in some cases vibrometer. A transducer system or vibration source consists of a piezoelectric transducer, a sonotrode which conveys the signal to the inspected part and a booster, which changes the signal [39]. To prevent hammering action on the surface of inspected part and harmonic generation, contact between transducer and inspected part should be maintained. For that purpose, sometimes a pneumatic cylinder can be used to press transducer against the inspected part. Holding the specimen in place especially during vibration excitation and inspection is very important in vibrothermography since it is an ultrasound process. For that purpose, clamps can be used. Between clamps and the specimen, rubber mounts can be placed to reduce the vibration effect of the mounting on specimen [17]. When excitation is applied to the specimen, the defected area will behave differently than the surrounding area which will be detected and visualized by vibrometer. IR or thermographic cameras are used for radiation detection in the range of 0.9-14 μm electromagnetic spectrum [40].

In most of the cases, a coupling media is strongly recommended to be inserted between the transducer and the sample to reduce the risk of specimen damaging, to place the specimen correctly, to increase quality of ultrasound transmission and to reduce the possibility of unwanted heat creation in the vicinity of excitation point [13]. In scientific literature, different coupling medias such as moisten fabric, aluminum or water-based gels have been used [15]. Zweschper et al. suggested using thin aluminum plate [41], Renshaw et al. used a business card or piece of cardstock [17], and Guo and Vavilov used 0.16 mm-thick piece of plastic as coupling media [42].

## 4. Types of Vibrothermography

Depending on oscillating amplitude and excitation frequency, vibrothermography can be classified as ultrasonic ultrasonic burst phase thermography, lock-in thermography and ultrasonic sweep or ultrasonic frequency modulated thermography [43, 44]. In ultrasonic lock-in thermography, a frequency of a few tens of millihertz is used to excite the part and produce a phase and an amplitude image [45]. On the other hand, in ultrasonic burst phase thermography, a single vibration pulse with a frequency of 20-40 kHz is used to heat the defect locally in a very short period of time [46]. When there is a subsurface defect in the specimen, defect surfaces will move relative to each other giving rise to a heat increase in this area which then be monitored by IR cameras [47]. Ultrasonic sweep or ultrasonic frequency modulated thermography is based on determining the thermal gradient change with respect to ultrasonic excitation at various frequencies in the range of typically 15 - 25 kHz and at constant vibration amplitudes [48, 49].

## 5. Vibrothermography Advantages and Disadvantages

All IR thermography methods are based on producing thermal gradient in the material and are constrained thermal diffusion rate within specimen. Apart from other IR thermography techniques where the heat has to travel from the surface to the defect area and return to the surface again, in vibrothermography, heat has to travel from the defect area to the surface only which make vibrothermography a very fast method [50]. Ibarra-Castanedo et al. compared different types of IR thermography techniques and stated that vibrothermography is capable of determining deeper damages than other techniques because in this technique, thermal waves have to travel shorter distances due to internal heat generation [51]. Surface-breaking and subsurface cracks with any orientation with respect to the surface of the part can be seen without the necessity for applying paint, or other emissivity-modifying coatings in vibrothermography [52]. Bolu et al. applied vibrothermography to defected and undefected turbine blades and stated that no apparent change in the resonance behavior of blades was observed which showed vibrothermography as a safe NDT method for turbine blades [53].

The general advantages of vibrothermography can be listed as follows [54, 17]:

- It can detect surface and sub-surface defects over a large area in a few seconds;
- It is a simple inspection method where the inspected parts often do not need cleaning;
- The probability of defect detection is high;
- It is sensitive to material thermal properties differences rather than material geometrical properties differences (scratches, high surface roughness, etc.) which is a real problem in most of other non-destructive inspection methods.

Despite these advantages, the widespread application of vibrothermography has been limited so far due to repeatability issue. Renshaw et al. stated that some permanent microscopic changes including fretting, plastic deformation, oxidation, adhesive wear and phase transformations can occur within the material in vibrothermography which causes the problem of lack of repeatability and suggested using minimum vibrational stresses [55]. The need for contact between the sample and the transducer is one of the most important challenge in vibrothermography. Since this contact is mostly made manually, the produced vibration spectrum is variable from contact to contact [56].

## 6. Materials and Probability of Detection

Vibrothermography can used in different industries and applications for defects detection in different materials. In aerospace applications, vibrothermography has been used in different parts made of CFRP, C/C-SiC and different metals [57]. Rantala et al. applied vibrothermography for defect detection in polymer and composite specimens. The results showed that material discontinuities, such as small cracks, voids and impact damages can be easily detected by using this technique [44]. Vibrothermography was successfully applied to Glass Reinforced Fiber Metal Laminates (GLARE) for detection of artificial defects [41].

Inspection capability or probability of detection of any non-destructive testing is very important for suitable selection of the method for the target material. The cracks in rigid and heavy metal structures are more difficult to detect due to their greater mass and stiffness, [58]. Favro et al. employed high frequency excited vibrothermography for detection of small fatigue cracks (about 0.7 mm in length) in aluminum and delaminations between plies in CFRP composite specimens [16]. Vertical fatigue cracks in aluminum alloy specimens, with 2 mm, 3 mm and 4 mm crack depths and with crack lengths of approximately 1.5 mm were successfully detected via vibrothermography [18]. Solodov et al. stated that aluminum aviation components can be inspected via vibrothermography with 11.6 kHz excitation frequency [59].

Mabrouki et al. stated that vibrothermography has capable of detecting surface cracks as short as 0.1 mm in steel plates [60]. Weekes et al. applied vibrothermography on airplasma sprayed CoNiCrAlY coated Inconel parts and concluded that cracks buried beneath a metallic coating remain detectable by vibrothermography, although they are less easily detected [61]. DiMambro et al. performed vibrothermography on 144 Ti64 specimens and 92 Inconel 718 specimens. These specimens had known fatigue cracks (0.016-0.182 inches lengths for Ti64 and 0.022-0.422 inches lengths for Inconel 718). They stated that for crack sizes 0.04 inches and more, vibrothermography came out to have higher probability of defect detection than FPI inspection [62]. Vibrothermography can be applied to detect as small as 20-micron long cracks in titanium fatigue samples [63].

Han et al. used vibrothermography for crack detection in a complex-shaped massive aircraft engine disk. They detected very small cracks (20 μm) in this study [64]. Almond et al. used laser spot thermography, eddy current thermography and vibrothermography for crack detection in metal parts. They stated that they detected corrosive cracks with 8 mm lengths and opening less than 1 μm in a last-stage steam turbine blade with vibrothermography technique [65]. Studies conducted by Montanini et al. revealed that 3.5 mm depth discontinuities below the surface can be detected with vibrothermography [46].

## 7. Principle of Heat Generation in Vibrothermography

As stated before, vibrothermography relies on heat generation in cracks due to excitation of the material with vibration pulse. Generally, three mechanism have been proposed for heat generation in cracks: frictional rubbing of crack surfaces / faces, plastic deformations due to propagation of cracks and viscoelasticity / material damping [66]. Many researchers simply labeled heat generation in vibrothermography as friction induced, but other researchers suggested that thermo-plastic heat generation or thermoelasticity, viscoelasticity and anelasticity, or a combination of these mechanisms are the sources of crack heating [67]. For instance, Montanini et al. stated that for flat-bottomed hole defects, viscoelasticity is the primary heat source, on the other hand the combination of viscoelasticity and friction is the primary heat source for elamination and cracks [68]. Vavilov et al. stated that friction between defect surfaces or plastic deformation are the main source of defect detection in composites [9]. Bai et al. stated that crack frictions and viscoelasticity are main contributions to the heat generation in vibrothermography [69]. The study conducted by Schiefelbein suggests that friction or adhesion are the main cause of heat generation in vibrothermography rather than plastic flow, linear absorption or thermoelasticity [67].

For frictional heating in crack faces, three relative motion modes were proposed in the literature (Fig. 3). It was suggested that the anti-plane shear mode (mode III, rubbing mode) and the tensile mode (mode I, clapping) might be the two modes responsible for the heat generation at the crack faces. It was also noted that the in-plane shear mode (mode II, rubbing) has very little contribution to the heat generation at the crack faces due to its significantly smaller relative magnitude when compared to the other modes [70].

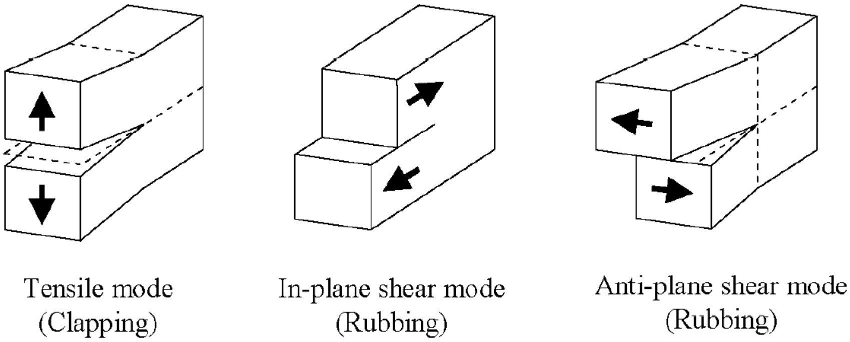

Fig. 3 Possible crack vibrational modes I to III (from left to right) [70].

In vibrothermography, if the parts go compression loading, the heating effect in crack closure tends to decrease due to limited friction between contacting faces [71]. On the other hand, Renshaw et al. have shown that under tensile loading of titanium, heat generation due to crack moves to the crack-tips without a heat generation in the central region. This is due to the fact that, under tensile loading, no relative movement toward the crack-tips and away from the crack-tips are observed. On the other hand, heat is generated due to the relative movement of contacting faces between these two regions [21]. The same conclusion was proposed by Weekes et al. when inspection of austenitic nickel super-alloy samples with vibrothermography [72].

Since determination of heat generation mechanism in vibrothermography is rather complex, artificial defects can be used to investigate the heat generation mechanism. Renshaw et al. used viscous material-filled synthetic defects in vibrothermography for heat generation. They stated that when the specimens were excited with resonant modes, honey filled drilled holes generated heat very efficiently when the beam vibrated in resonant modes [73].

## 8. Factors That Affect Vibrothermography Performance

Table 1 shows vibrothermography measurements for different materials and technical details of these experimental studies performed in literature. There are several factors that affect defect detection in vibrothermography: excitation frequency, crack size, loading mode, dynamic stress, crack closure etc.

Excitation frequency and amplitude of the vibration are two key parameters in successful detection of cracks in vibrothermography. For efficient crack detection, sufficient amplitude vibrations should be used. On the other hand, when high amplitude vibrations are used, specimen may be damaged [74]. Experimental studies have shown that metal parts depend highly on frequency when inspected [75]. Holland et al. showed that when frequency is increased, heat generation also increases in fatigue cracks detection [76]. On the other hand, Qingju et all. stated that the higher frequency results in noisier phase image. Therefore, it is hard and sometimes impossible to detect defects for larger frequencies [77]. Song and Han studied the effect of frequency on crack detectability in vibrothermography. They used three different frequency (20, 30 and 40 kHz) on Al bars. They concluded that when frequency is increased, acoustic energy and detectability of cracks decrease [78].

Due to convenience and commercial availability, fixed frequency excitation is commonly used in most of the studies. However, it has been demonstrated that each defect has a particular resonant frequency, referred to as the local defect resonance (LDR), at which its response will be maximized. For instance in a study conducted for defect detection in 28 x 13 cm graphite epoxy beam, it was revealed that two artificial and embedded defects of 10 x 7 mm and 7 x 7 mm sizes can be seen only between 13.5 and 15.0 kHz excitation frequencies [79]. For overcoming this problem, one promising approach is finding LDR values of defects via FEM analysis and stimulating the material with these values or using multi-frequency excitation [80]. By using this method, different defects with different sizes can be detected by changing the vibration at related LDR frequency [81-83]. For distinguishing damaged regions from surroundings, multi-frequency excitation is a very useful method which enables that the resulting heat generation covers the whole length of the material [84, 85]. There are two advantages of multi-frequency excitation; first, reducing the number of excitation locations needed to form a complete picture of the defects present within a material; and second, reducing the number of blind zones that cannot be detected with single frequency implementation [86].

There are two other factors which affect crack detectability in vibrothermography: the crack closure amount and closure stresses distribution between crack faces [21]. If the crack surfaces are too close, then the relative motion between crack faces will be limited and heat generation at defects will not be enough for detection by IR camera [17].

Low surface emissivity is also a very important thermal property which can reduce the detectability of cracks in vibrothermography [17].

Type of mounting, excitation point location, pressure applied against mounting faces, and quality of coupling quality are main factors which are responsible for proper crack detection in vibrothermography [42]. For sample mounting methods, Xu et al. conducted vibrothermography experiments on a thin aluminum beam where three cracks were located in different locations. They suggested that for these types of thin specimens, double fixed ends configuration is the best way for detecting of cracks [87]. For holding pressure, Min et al. concluded that when engagement force increases, the temperature rise also increases [88]. For the location of the excitation point, Liu et al. stated that this location should be closer to the defects which are located at greater depth from the surface [89]. For coupling media, Song et al. compared duct tape and leather tape and stated that the duct tape is better than leather tape [78]. Bolu et al. performed vibrothermography inspection on high strength Nickel alloy turbine blades and stated that a general increase in the temperature rise can be seen with an increase in the horn static force, vibration amplitude and excitation time. Also, they tried gaffer tape, Silicone tape, electrical tape, paper and duct tape as coupling material and concluded that maximum temperature rise was seen with electrical tape, followed by gaffer tape [90].

Power, excitation duration and distance between sample and the horn also affect detectability of cracks in vibrothermography. Sathish et al. stated that when excitation power was increased from 500 to 1000 W, the highest temperature that the specimen gained also increased if distance between sample and the horn and excitation time were fixed. When excitation duration was increased from 250 ms to 1000 ms, then the highest temperature that the specimen gained also increased if power and distance were fixed. If distance between sample and the horn increased, change in maximum temperature decreased exponentially power and excitation duration were fixed. They suggested that larger distance between horn and sample, longer excitation time and minimum excitation power should be used in applications [91].

Table 1. Vibrothermography measurements for different materials and technical details

| Material | IR Camera | Vibrometer | Excitation Frequency | Excitation Power | Excitation Time | Reference |
|---|---|---|---|---|---|---|
| CFRP | InSb Flir Phoenix | - | 20 kHz | - | - | [15] |
| AISI 304 | Cedip Titanium 560 M | Polytec PSV-400-H4 | 15.5-19.5 kHz | 350 W | 20 s | [16] |
| Graphite cast iron | Titanium 560 M, Flir Systems | PSV-400-H4, Polytec GmbH | 15-25 kHz | 0-2.2 kW | | [46] |
| AISI 304 | Cedip Titanium 560 M | Polytec PSV-400-H4 | 15-25 kHz | 0-2.2 kW | 20 s | [47] |
| S355 steel | Flir Phoenix | - | 15-25 kHz | - | - | [48] |
| Ti64 and Inconel 718 | Phoenix-MWIR 9803 | - | 40 kHz | - | 800 ms | [62] |
| Austenitic nickel super-alloy | Merlin Indigo | - | 40 kHz | 400 W | - | [72] |
| Aluminum | - | OFV 511 | 20, 30, 40 kHz | 750, 800, 1000 W | - | [78] |
| GFRC | InfraTec VarioCam hr | Polytec PSV-400 | 0-1600 Hz | - | 5 min | [84] |
| Aluminum | FLIR E60 | - | 40.7 kHz | - | 1-2 s | [87] |
| C45 ferritic steel | FLIR T640 | - | 0.4 Hz | - | 5 s | [88] |

Table 2. (Con.) Vibrothermography measurements for different materials and technical details

| Material | IR Camera | Vibrometer | Excitation Frequency | Excitation Power | Excitation Time | Reference |
|---|---|---|---|---|---|---|
| CFRP | Flir Phoenix | - | 15-25 kHz | - | 10 s | [89] |
| Ti-6 Al-4V | Merlin Mid-IR, Indigo Inc. | Polytec -PSV-400, OFV-5000 | 20 kHz | 1000 W | 250-1000 ms | [91] |

| | | | | | | |
|---|---|---|---|---|---|---|
| Nickel based superalloy | Cedip Jade | - | 20 kHz | 400 W | 0.5 s | [92] |
| Inconel 100 | Indigo Merlin-Mid | Polytec PI, sensor head: OFV 353, controller: OFV 3001 | 20 kHz | 2000 W | - | [93] |
| CFRP | Indigo Merlin MWIR | - | 40 kHz | 1 W | 0-30 s | [94] |
| Tungsten carbide | InSb Phoenix Indigo | - | 15-25 kHz | - | 0.8 ms | [95] |
| Nickel based superalloy and mild steel | Cedip Jade | - | 40 kHz | 400 W | 0.4-0.6 s | [96] |
| 2024-T3 Aluminum | FLIR ThermaCAM SC 3000 | - | 10 Hz - 20kHz | - | - | [97] |
| Metal | CEDIP/FLIR Silver 420M | - | 35 kHz | .2-2 kW | 50-3000 ms | [98] |
| Aramid composite | FLIR SC 7600 | - | 35 kHz | 80-130 W | 5 s | [99] |
| CFRP | IRCAM Equus 327 | Polytec PSV 300 | 0-100 kHz | - | 30 s | [100] |
| CFRP | InSb Phoenix Indigo | - | 20 kHz | - | 5 s | [101] |
| GFRC | InfraTec VarioCam hr | Polytec PSV-400 | 0-1250 Hz | - | 5 min | [102] |
| CFRP | FLIR A6750sc | Polytec PSV-500-3D XTRA | 1-250 kHz | - | 0-50 s | [103] |
| CFRP | FLIR A6750sc | Polytec PSV-500-3D XTRA | 1-250 kHz | - | 50 s | [104] |
| VHB3914 and VHB3095 | FLIR SC6000 | - | 12-30 kHz | - | - | [105] |

## 9. Conclusions

The main aim of this study is to give researchers recent developments and state of the art in vibrothermography. Some of the main conclusions can be given as follows:

- A coupling media between sample and transducer is strongly recommended to be used in vibrothermography testing. Thin plastic tape, gaffer tape, silicone tape, electrical tape, paper and duct tape can be used as coupling media;
- Heat generation is attributed to frictional rubbing of crack faces, plastic deformations due to crack propagation and viscoelasticity / material damping but as stated in most of the studies, frictional heating is the most dominant factor in heat generation in vibrothermography;
- Using single frequency excitations could result in blind zones where defects cannot be detected. Multifrequency excitation is a good alternative to solve this problem

where part is excited with different LDRs so that various damage features can be detected;

- A crack with 0.7 mm length in aluminum plates, 0.1 mm length in steel plates, 1 mm length in Ti64 and Inconel 718 plates can be successfully detected by vibrothermography;
- In vibrothermography, amplitude vibrations should not be high to prevent the specimen from damage. It should not be very low either for proper defect detection;
- The material being detected need to have high surface emissivity for proper defect detection.
- For proper defect detection in vibrothermography, the specimen needs to be fixed with double fixed ends configuration and pressed with high engagement force and excitation point should be closer to the defects;
- Larger distance between horn and sample, longer excitation time and minimum excitation power should be used in vibrothermography applications;
- Vibrothermography is less sensitive to surface roughness than other non-destructive inspection methods. Complex shapes produced by Additive Manufacturing (AM) is, in one aspect, an advantage for this technology, but in terms of inspection, it is a challenge. High surface roughness of AMed parts is one of the biggest problems in the inspection of these parts. Vibrothermography seems to be a good alternative to conventional methods in the inspection of AM parts and it could eliminate the necessity of post processing of AMed parts. But to the best of author's knowledge, there is no data yet on background response of rough as-built surfaces and the challenge of inspecting internal features with no line of sight in AM parts.

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