Application of Vibrothermography in Nondestructive Testing of Structures

M. SZWEDO, L. PIECZONKA and T. UHL

ABSTRACT

Vibrothermography is a nondestructive testing method that monitors heat produced by damage under vibration and/or ultrasonic excitation in order to evaluate the structural health. The paper investigates practical aspects of vibrothermographic testing of structures. Measurements in two typical application areas of vibrothermography are presented and discussed. The examples are weld test specimens and a military aircraft fuselage skin. Measurements have been performed with use of an in-house vibrothermographic testing system. In case of welded specimens a series of carbon steel test samples with different flaw types have been investigated. In case of aircraft testing, field measurements have been performed on a wing and fuselage sections in order to assess the structural integrity. The paper discusses practical aspects related to field measurements with use of vibrothermography and presents thermal image processing techniques which allow to obtain the best flaw detection results. Applied image processing techniques allow increasing the quality and readability of the results coming from field measurements with low thermal response from the structure. The paper is concluded with a discussion on applications of vibrothermographic testing in Structural Health Monitoring applications.

M. Szwedo[1], L. Pieczonka[2], T Uhl[3], Department of Robotics and Mechatronics, Faculty of Mechanical Engineering and Robotics, AGH University of Science and Technology, Al. A. Mickiewicza 30, 30-059 Krakow, Poland,

1. e-mail: szwedo@agh.edu.pl
2. e-mail: lukasz.pieczonka@agh.edu.pl
3. e-mail: tuhl@agh.edu.pl

INTRODUCTION

Thermography is a family of nondestructive testing methods based on temperature measurement and evaluation to reveal structural damage. All thermographic methods can be divided into two major groups, namely the passive and active approaches [1]. Passive methods rely on temperature measurements without introducing any external excitation. These methods are typically qualitative and provide global information on potential anomalies. In contrast, active methods require external or internal excitation. The former often uses halogen or flash lamps to heat up a surface of monitored structures. The latter utilizes ultrasound or inductive heating for internal heat generation.

Vibrothermography is a nondestructive testing method that monitors heat produced by damage under vibration and/or ultrasonic excitation in order to evaluate the structural health (Figure 1). The method has been originally proposed by Hennecke et al. [2-3] in the late 80ties, but popularized by Favro et. al. [4] almost twenty years later. In scientific literature, vibrothermography is also referred to as: ultrasonic infrared thermography, acoustic thermography, thermosonics, sonic IR, elastic-wave-activated thermography, thermal vibration method or vibroIR. The gap between the original work of Hennecke et. al. and widespread interest in the method, after the publication of Favro et al., is due to several factors one of the most important being the availability of more efficient and affordable infrared cameras that are necessary to perform measurements. Despite many research efforts, over the last thirty years, the main issues of concern in industrial application of vibrothermography are still reproducibility and reliability of measurements. The mechanisms of vibration energy dissipation on damage are not yet fully understood but certainly depend on the material parameters and defect characteristics [5-9]. Therefore the exact amount of heat that is expected to dissipate on certain defects is not known a priori. Nevertheless it is known that generated heat depends on frequency and position of the excitation source. Recently, vibrothermography has been gaining more attention in various damage detection investigations [10-15]. In particular it has been applied for crack detection in metallic components [10-13] and detection of damage in composite materials [14-15] among other applications. In parallel to experimental investigations also numerical simulations of vibrothermography aiming at explaining physical phenomena behind the heat generation are being investigated [16-19].

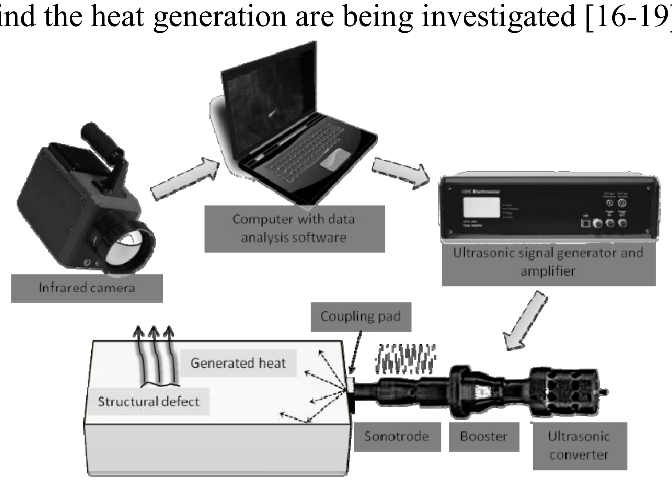


Figure 1. Operational principle of vibrothermography.

Developed diagnostic system based on vibrothermography

The diagnostic system based on vibrothermography has been developed at AGH-UST within the scope of the research project MONIT - Monitoring of Technical State of Construction and Evaluation of its Lifespan. The complete diagnostic system has been developed and built in two versions: (1) stationary system for laboratory tests and (2) handheld system for field measurements. The systems are schematically depicted in Figure 2.

The stationary measurement system is equipped with pneumatic press system which allows controlling clamping force between the excitation device and the structure. Supporting frame is fully customizable, depending on the type of components to be tested, it can be designed to meet the requirements. Handheld version of the ultrasonic excitation device comprises a holder that has been designed to allow easy operation and mobility.

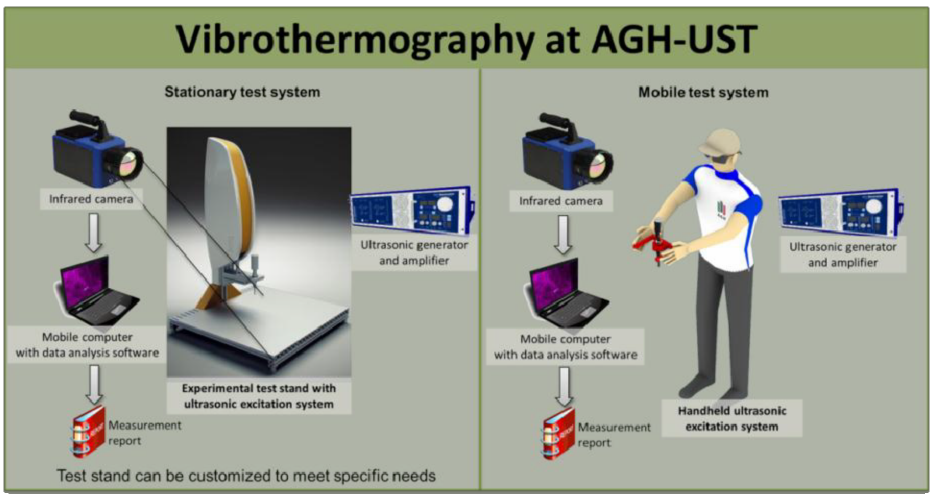


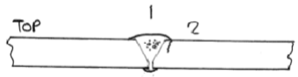
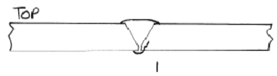
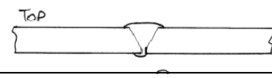
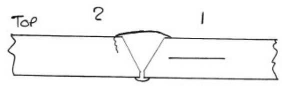
Figure 2. The laboratory (stationary) and mobile (handheld) vibrothermography systems.

INVESTIGATION OF WELD TEST SPECIMENS

One of the application areas of vibrothermography is the detection of cracks in metals. A set of carbon steel weld specimens with known defects have been tested to verify detection capabilities of the developed vibrothermographic system. Four different defect types were present in the samples: (1) root crack, (2) lack of fusion, (3) lamination and (4) porosity, as identified with the standard ultrasonic inspection. For each sample the localization, types and sizes of defects have been identified and documented. The results of ultrasonic inspection are presented in the Table 1.

Stationary vibrothermographic test system has been used with the CEDIP/FLIR Silver 420M research infrared camera. Ultrasonic excitation device with 35 kHz central frequency has been used for the tests. The experiments have been carried out for different power levels of ultrasonic excitation (ranging from 10 to 100% of full device power of 2 kW) and different excitation times (ranging from 50ms to 3000ms).

Table 1. Defects indentified in test specimens by means of ultrasonic inspection.

No.	Flaw Type	Weld/Specimen Cross Section(s)	Detection status
1	Porosity		Not detected
	Toe Crack		Detected
2	Root Crack		Detected
	Lack of Root Fusion		Detected
3	Lamination		Not detected
	Toe Crack		Detected

For each experiment a sequence of the thermal images has been acquired. Subsequently the data has been post processed with image processing algorithms for noise removal and image enhancement. Initial stage of post processing included the removal of fixed pattern noise (FPN), bad pixels and vignetting effects [20]. In the second stage image enhancement techniques were applied. Thermal contrast based techniques have been used as they are the most common approaches of processing thermal images [1]. Additionally, other techniques including gradient estimators, frequency domain image filtration and region intensity statistical analysis were used to obtain comprehensive information about defects. As a result of vibrothermographic investigations the toe crack and root crack defects have been successfully detected.

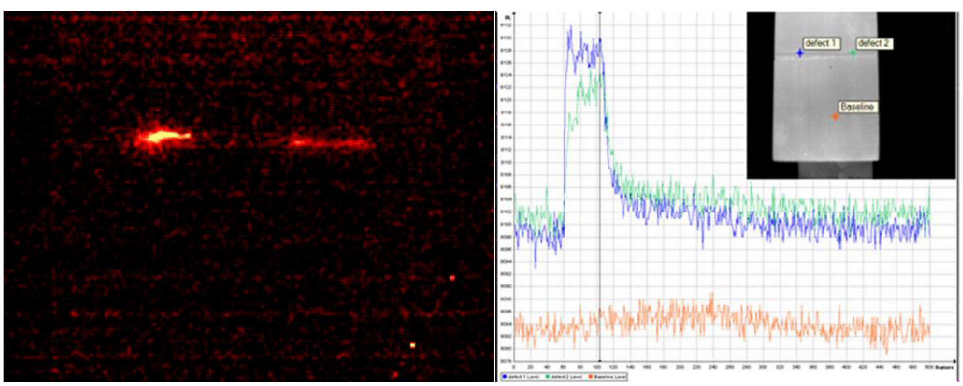


Figure 3. Exemplary detection result from vibrothermographic test.

Localizations and sizes of defects were obtained after thermal image processing and analysis as shown in Figure 3. Porosity and lamination type defects have not been detected with the assumed experimental setup. It is known that voids and porosity type defects are hardly detectable by vibrothermography as this type of damage does not cause frictional energy dissipation under ultrasonic loading. Therefore the lack of detection has been considered probable in this case. The lamination defect, on the other hand, was expected to be revealed in vibrothermographic test. In the conducted experiments it has not been the case most likely due to the insufficient power of the applied ultrasonic excitation. Because of that and of the thermal diffusivity of steal, the portion of heat that has been generated on the defect did not propagate to the surface of the sample in the amount sufficient for successful detection.

MILITARY AIRCRAFT FUSELAGE SKIN TESTING

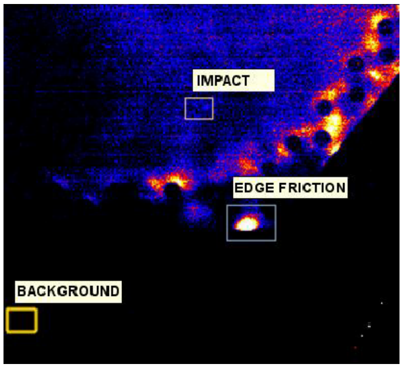
Fuselage panels and connecting parts of a jet fighter aircraft have been diagnosed with the developed handheld inspection system. In particular barely visible impact damage has been investigated. Vibrothermographic test has been performed on a composite wing panel before and after introducing a small impact damage. Tests have been conducted on a wing panel close to the wing root, which was made of fiberglass.

Thermal responses of the ultrasonically excited panels have been acquired with CEDIP/FLIR Silver 420M research infrared camera.

The use of handheld ultrasonic excitation devices is required in case of field measurements where portability of the measurement system is of importance. This allows application of excitation in specified localization on the structure in order to deliver sufficient amount of energy for heat generation and damage detection.

There are, however, certain measurement issues related to this type of excitation. The most severe is the problem of non-homogeneity of excitation. Due to the varying contact pressure and misalignment between the sonotrode and the test piece the intensity of ultrasonic excitation is fluctuating with time. In case of a handheld device the contact pressure and the alignment of the sonotrode tip on the test sample cannot controlled as precisely as in case of a stationary press system. This results in fluctuating and possibly non-monotonic thermal responses from the structure. As a result the localization of damage and estimation of its size may be impaired. As a solution to this problem the image processing technique based on a two dimensional Fourier transform of the infrared images has been proposed by the authors in [20]. This image processing technique allows increasing the quality and readability of the results coming from a vibrothermographic measurement with poor and non-homogenous ultrasonic excitation.

Impact damage in a glass fiber composite panel has been investigated. As can be seen in Figure 4 the damage that has been introduced in the plate has been detected. An interesting observation has been made regarding the heat sources that caused temperature rise in the measured area of the plate. Friction between panels and energy dissipation in the elastomeric material that has been used in the connection area between the skin panel and the wing frame caused measurable temperature rise on the panel that was not attributed to damage. In this case the problem has been identified by a detailed analysis of the test structure. This should be, however, a warning for future investigations and for the approaches directed at developing automated damage detection algorithms.



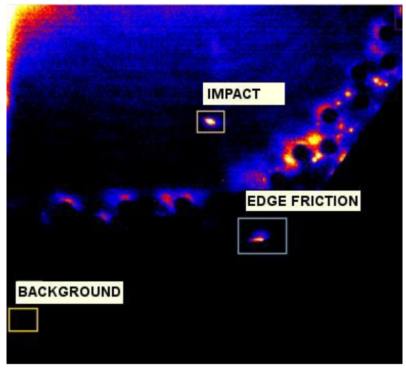


Figure 4. Infrared images of the panel in the initial state (left), after introducing impact damage (right).

To conclude this example it can be stated that it is feasible to perform vibrothermographic testing in field conditions. The proposed image processing technique can be successfully applied to improve the post processing of infrared images acquired from vibrothermographic field test with handheld excitation device.

CONCLUSIONS

Results that have been obtained show that vibrothermography is a valuable nondestructive testing method. Developed diagnostic system has been tested in both laboratory and field conditions. Measurements performed to date give very good results as compared with the classical damage detection methods. Vibrothermography should be seen as a fast and reliable inspection technique that can be used for the assessment of technical condition of various types of engineering structures.

Conclusions that arise from performed laboratory and field experiments are the following:

- Vibrothermography is capable of competing with the classical inspection techniques, despite its known limitations.
- Both laboratory and field tests have proven the good efficiency of the method in discovering structural damage.
- An image processing technique has been successfully applied to enhance a low quality infrared image sequence, caused by poor ultrasonic excitation, to obtain satisfactory damage detection results. Detailed description of the image processing algorithm has been presented by the authors in [20].
- Results of thermal image processing obtained with the proposed algorithm bring more accurate and better quality information about the structural health of tested components from the low quality input data.

Described diagnostic system is being marketed by a newly established spin-off company of the AGH UST called MONIT SHM LLC [21].

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