VIBROTHERMOGRAPHY - MEASUREMENT SYSTEM DEVELOPMENT AND TESTING

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Summary

The paper investigates practical aspects of vibrothermographic testing. 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. Detailed description of a prototype measurement system, that has been developed, is given together with the description of preliminary tests on a composite specimen. The parameters that influence the efficiency of damage detection in vibrothermography have been investigated in more detail. Presentation and discussion of the results is given in the paper.

Keywords: SHM, NDT, vibrothermography, damage detection.

WIBROTERMOGRAFIA - ROZWÓJ I TESTOWANIE SYSTEMU POMIAROWEGO

Streszczenie

Artykuł omawia praktyczne aspekty pomiarów metodą wibrotermografii. Rozważana metoda pomiarowa bazuje na pomiarze temperatury generowanej w miejscach występowania uszkodzeń w strukturze pod wpływem wymuszenia drganiowego i/lub ultradźwiękowego. Artykuł zawiera szczegółowy opis prototypowego stanowiska badawczego oraz wstępnych testów przeprowadzonych na płycie kompozytowej. Ponadto przeprowadzono analizę wpływu niektórych parametrów pomiarowych na wydajność wykrywania uszkodzeń omawianą metodą. Wyniki badań oraz ich analiza przedstawione są w niniejszym artykule.

Słowa kluczowe: SHM, NDT, wibrotermografia, detekcja uszkodzeń.

1. INTRODUCTION

Structural Health Monitoring plays an increasing role in contemporary engineering [1-3]. This fact can be attributed to several factors. Firstly, the critical failures resulting in loss of life that are discussed by the mass media motivate the regulatory agencies to demand some form of structural health monitoring of the infrastructure. Secondly, the aging infrastructure that, especially in European conditions, operates beyond its designed life period needs to be monitored in order to avoid fatal damages and to reduce maintenance costs. Other important factors include the increased availability of affordable measurement equipment and damage detection techniques that provide the means for implementation of SHM procedures in industrial applications. In recent years a number of different damage detection methods have been developed [1-3]. The success of these methods often depends on three major factors, namely: (1) on the simplicity of interpretation of the result that they provide, (2) on the necessity to use the baseline reference data (measured in undamaged state), (3) on the cost and complexity of their implementation. A group of methods particularly advantageous in all three aspects is infrared thermography [4-5]. This family of NDT techniques is based on temperature measurements to reveal structural damage. Infrared thermography can be divided into two categories: passive methods and active methods. Of special interest in the group of active methods, due to its efficiency, is vibrothermography that is considered in this paper.

2. THEORETICAL BACKGROUND OF THE METHOD

Vibrothermography, also known as thermosonics, sonic IR or ultrasonic thermography is a special deployment of active thermography that uses mechanical vibration excitation [4-6]. Excitation signal can be can be applied in various forms. The most popular being the ultrasound burst thermography, lock-in thermography and continuous thermography [5-6]. In ultrasound burst thermography, as shown in Fig. 1, a burst ultrasonic signal is applied on the transducer to induce stress waves in a test structure. Periodic stress waves propagating in a structure cause frictional sliding at discontinuities (e.g. delaminations, fatigue cracks) and therefore the conversion of mechanical energy into thermal energy generating heat. Thus, the heat source in vibrothermography, unlike in other thermographic techniques, is the discontinuity itself, which makes the identification of defects simpler.

Heat generated at discontinuities propagates to the surface where temperature change is measured by a sensitive infrared camera. Typical infrared cameras that are used for this type of tests measure electromagnetic radiation in the Medium Wavelength Infrared (MWIR) spectrum, i.e. from 2.5 to 5 μm. Diagnostic information is evaluated from the acquired data by means of customized image processing algorithms. Theoretical considerations regarding the nature of energy dissipation mechanisms and heat propagation are outside of the scope of this paper and an interested reader can find more information in [4-7].

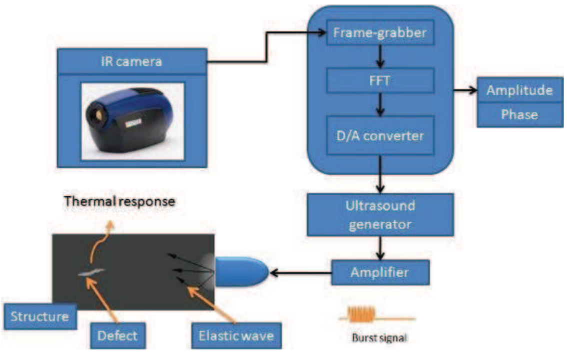

Fig. 1. Ultrasound burst thermography

The excitation is typically applied using an ultrasonic device as depicted in Fig. 2. that comprises three elements: (1) converter - a bolt clamped Langevin type transducer that allows for a high power and narrowband frequency operation; (2) booster - a metal piece (typically aluminum or titanium alloy) that is used to clamp the entire ultrasonic assembly and to amplify vibration amplitude; (3) sonotrode - an element that comes into contact with inspected structure and further amplifies vibration amplitude. When designing such ultrasonic device it is important to remember that specific natural frequencies of these elements have to be perfectly matched for proper operation.

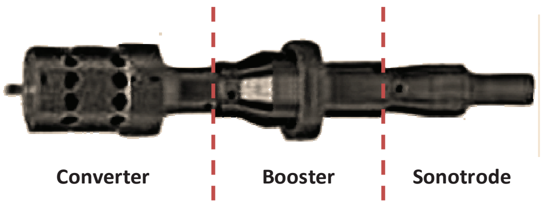

Fig. 2. Ultrasonic assembly

Vibrothermography is a wide area noncontact measurement technique. The component to be tested does not have to be dismantled from the structure and accessibility from only one side is sufficient. Additional advantages of the method include short measurement time, easy interpretation of the detection results. Under ultrasonic excitation damaged areas become heat sources which improves the contrast of obtained thermal images. The drawbacks of the method include the inability to detect voids in the material which do not dissipate ultrasonic energy and a potential risk of damaging sample's surface (e.g. paint or varnish coating) under the sonotrode if the power of ultrasonic converter is set too high for a particular test sample.

3. DESCRIPTION OF THE MEASUREMENT SYSTEM

A prototype system for vibrothermographic testing has been developed at AGH-UST within the scope of the research project acronym MONIT [8].

The system consists of four main components:

- High sensitivity infrared camera;
- Ultrasonic signal generator and amplifier;
- Ultrasonic excitation assembly;
- Mobile computer for image acquisition and control of infrared camera and signal generator.

The system has been developed in two variants as shown in Fig. 3. Both variants share the four abovementioned basic components but differ in the design of the bearing structure. The first variant, depicted Fig. 3a, is a stationary system designed for laboratory use. The bearing structure is composed of a light aluminum frame, pneumatic press system and fixture for the ultrasonic excitation assembly. The second variant, depicted in Fig. 3b, is a mobile system for field measurements. The bearing structure in this case has been reduced to a fixture for the ultrasonic excitation assembly with an ergonomic hand grip for easy operation.

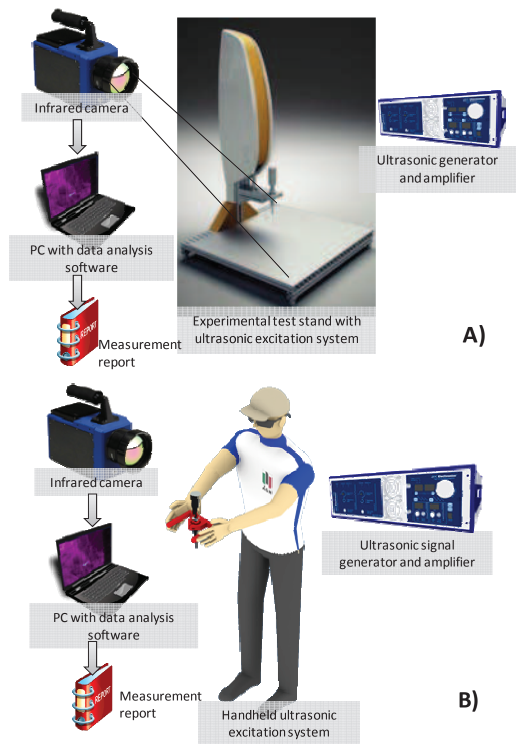

Fig. 3. Developed measurement system. Stationary version (A) and mobile version (B)

The main parameters of the constituent components of the measurement system are briefly summarized below. The parameters have been initially specified after an extensive literature study and preliminary numerical and experimental investigations.

Infrared camera that has been chosen for the system is a cooled detector MWIR camera. The main parameters of this camera are summarized in Table 1.

Table 1. Characteristic parameters of the infrared camera

Sensor type	InSb
Sensor resolution	320x256
Spectral range	2.5 - 5μm
Frame rate	Up to 380Hz
NETD	<25mK
Interface	USB / CameraLink

Ultrasonic signal generator and amplifier has been designed in close cooperation with a local electronic systems manufacturer, to meet the specific needs of vibrothermographic measurements. High voltage and high power output were required for proper operation of the ultrasonic excitation system. Signal generator had to be equipped with a frequency tuning circuit to match the working resonant frequency of the transducer assembly. Moreover appropriate trigger outputs had to be designed to allow for seamless operation with the infrared camera. Trigger outputs were also necessary for lock-in measurement configurations. All parameters of the signal generator and amplifier are controllable from the software layer. The main parameters of the prototype design are summarized in Table 2.

Table 2. Parameters of the designed ultrasonic generator and amplifier

Frequency range	20 - 50 [kHz]
Output power	1.5 [kW]
Trigger output	TTL
Control interface	USB (Matlab, C/C++ library, dedicated application)
Output signal options	Continuous, Burst, Modulated

Considered design of the **ultrasonic excitation assembly** allows for high power narrowband frequency operation. Because of changing wavelengths of the elastic waves and changing maximum output power possible at different frequencies it has been decided that two ultrasonic assemblies should be used. Assemblies with central working frequencies of 20kHz and 35kHz have been prepared. Both assemblies can be used in stationary and mobile versions of the measurement system and are powered by the designed signal generator and amplifier. The choice of the assembly to be used depends on the characteristics of the test structure, mainly on its material, overall dimensions and mass.

Software framework for processing the acquired infrared images has been also prepared. Developed software procedures allow to acquire, enhance and post process infrared image sequences in order to obtain valuable diagnostic information. Additionally, software tools that allow setting up measurement parameters have been prepared. It is possible to control the parameters of the signal generator and amplifier as well as the parameters of the infrared camera.

The main software modules that have been implemented include the following:

- Thermographic image acquisition from infrared camera;
- Pre- and post- processing of thermal images (filtering, image transformations, advanced spectral processing);
- Image analysis (point, line and area statistical operations);
- Signal generator control;
- Reports generations (thermal images, processing and analyzing results, comments, system configurations and parameters could be reported).

Stationary configuration of the test system allows to control the contact pressure between the sonotrode and a test piece. It is also possible to measure the dynamic force during operation of the ultrasonic assembly. This unique feature allows to collect measurement data that can be subsequently used to perform a virtual test and validate a numerical model.

4. EXPERIMENTAL TESTING

Experimental testing of the developed prototype has been performed in order to find optimal ranges of operational parameters. Multiple tests have been performed on different test specimens using both stationary and mobile versions of the developed system. Hardware platform and software procedures had to be verified on laboratory test specimens with known damage parameters, before the procedures could be applied for damage detection in real working conditions.

The following main parameters of the system have been tested:

- Dependence of the temperature gain on damaged area on the power of ultrasonic converter;
- Dependence of the temperature gain on damaged area due to changes in contact pressure between the sonotrode and the specimen;
- Dependence of the temperature gain on damaged area on the type of coupling material.

Design of Experiments (DOE) has been performed in order to find the most suitable configurations of measurement parameters. Box-Behnken design has been prepared for three parameters of the measurement system, namely: the power of ultrasonic converter, contact pressure between the sonotrode and the test specimen, excitation time. Box-Behnken design has been chosen for this preliminary study because it provides good exploration of the parameter space and at the same time is very economical in terms of the number of sampling points [9].

Composite plate made of carbon epoxy prepreg 950-GF3-5H-1000 has been used as a test case (see Fig. 4). The plate has been damaged in a with low velocity impact event. The result was a matrix and fiber cracking in the vicinity of the impact location.

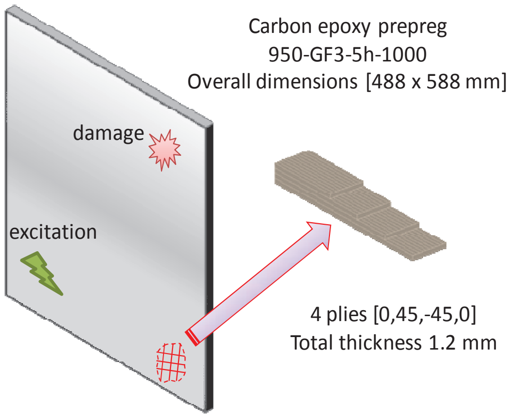

Fig. 4. Analyzed test specimen

Field of view of the infrared camera was set to the upper left corner of the plate where the defect was located. The plate was excited in a lower left corner i.e. on the diagonal from damage. Excitation location was outside of the field of view.

Sample thermal image of the damaged area of the plate, acquired during vibrothermographic test is shown in Fig. 5. Star shaped marker indicates the location for which the subsequent comparisons have been performed. Image processing and analysis techniques as implemented in the developed software framework have been used for subsequent analyses. Implemented thermal images processing can be used to estimate sizes and localizations defects in tested component. Advanced processing of image data could be used for further diagnostics and monitoring algorithms and application [7].

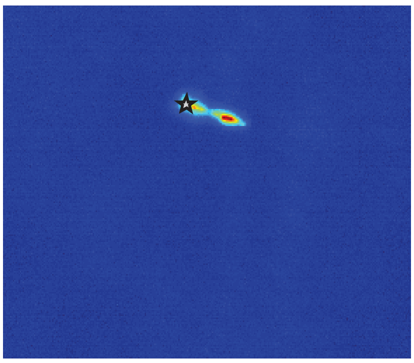

Fig. 5. Thermal image of damaged area

According to the prepared DOE plan, experimentation has been performed on the test specimen. Performance metric that has been considered was a maximum gain in temperature for a chosen point on damaged area (marked with a star in Fig. 5). The quality of vibrothermographic test is dependent on the amount of heat generated at structural defects. The more vibration energy is dissipated on defects the better is the contract of the thermal image. Thus evaluation of damage parameters is easier.

All experiments in the DOE plan have been performed according to the same measurement plan composed of four main steps:

1. Stabilization of the temperature of the test piece to a reference ambient temperature (21ºC);
2. Synchronized start of the ultrasonic excitation and data acquisition with IR camera;
3. Acquisition of thermal images for 10 seconds;
4. Post-processing of the acquired image sequence.

Influence analysis has been performed on the results obtained from experimentation in order to identify the most important factors responsible for thermal response. First order effects have been computed for the three process parameters. Results are shown in Fig. 6. It can be seen that the most important factor is the contact pressure between the sonotrode and the test piece. This parameter is representative for the transfer of ultrasonic energy generated by the converter to the test specimen. Measurement time and power of the ultrasonic converter also influence the amount of energy dissipated by damage. The longer is the measurement time the more energy is transferred into the test specimen and thus better thermal response. Clearly enough the power generated by the ultrasonic converter also influences thermal response. The most important observation that has been made is the fact that the coupling between the ultrasonic assembly and the test piece is the most influential measurement parameter.

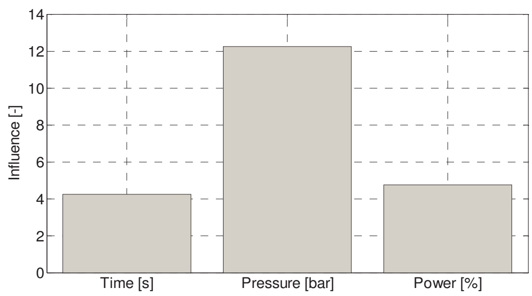

Fig. 6. Influence analysis of measurement parameters

According to literature survey, coupling between the ultrasonic assembly and the test specimen is indeed one of the most important measurement parameters [10]. Certain configurations of coupling pads and coupling pressure can produce an effect described as 'acoustic chaos' [11]. This effect allows to obtain broadband excitation of the structure with use of narrowband ultrasonic converter typically used in vibrothermographic measurements.

Additional experimental tests have been performed to analyze the influence of the pressure between the sonotrode and the plate. As previously stationary version of the system has been used to perform measurements. Different pressure applied to the pneumatic press system produced different contact force between the sonotrode tip and a surface of a test piece. Force in the range from 0.01 to 2.76 kN has been considered in fourteen increments. It is important not to apply force that could destroy the surface of the test specimen. Applied thrust force should not exceed the blocking force of the piezoceramic stack inside the ultrasonic converter. This is important especially for low power operation.

Differences in thermal responses obtained for measured configurations can be seen in Fig. 7. Temperature evolution on damaged area (marked with a star in Fig. 5) shows significant differences between measured configurations.

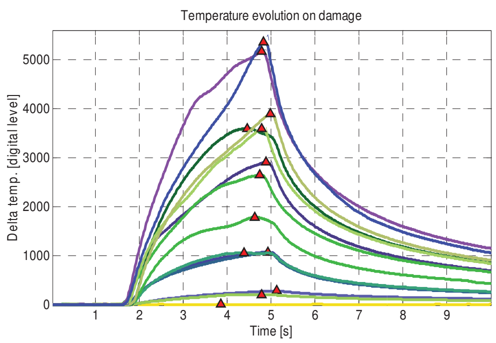

Fig. 7. Temperature evolution on damage for different interface forces

Fig. 8 presents maximal temperature gain measured in considered point. It can be seen that the pressure between the sonotrode and the test specimen is directly proportional to the measured thermal response.

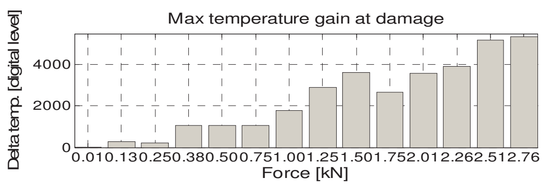

Fig. 8. Maximum temperature gain on damage for different interface forces

Additional tests have been performed to check the influence of the power applied to the ultrasonic converter on the measured thermal response. The initial assumption was that the energy delivered to the ultrasonic converter is directly proportional to the vibration energy delivered to the test specimen and hence to the energy dissipated at structural defect. Power ranging from 20% to 80% of the maximum power that the ultrasonic converter could provide have been tested. Maximum available power output has not been used as it could damage the surface the composite plate. As expected, it is clearly visible in Fig. 9 that with an increasing power of the ultrasonic transducer thermal response is also increasing.

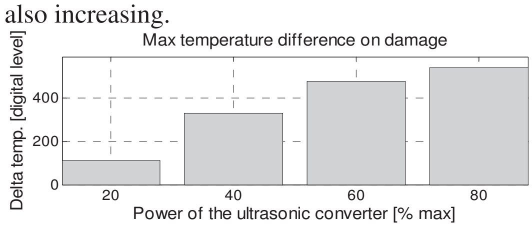

Fig. 9. Maximum temperature gain on damage for different power levels of ultrasonic converter

As the last step in the analysis of the prototype measurement system different cupling pads have been tested. Coupling pad is applied between the sonotrode and the surface of tested object in order to improve impedance match between the two and to protect the surface of the test specimen. Based on a literature study four materials typically used for as coupling have been tested, namely: rubber, felt, woven fabric and paper. The same measurement parameters have been used in each case. Differences in the obtained thermal responses are depicted in Fig. 10. It can be seen that the type of coupling influences measured thermal response. More detailed study has to be, however, performed in order to verify the influence of coupling material in connection with the applied contact pressure and ultrasonic power.

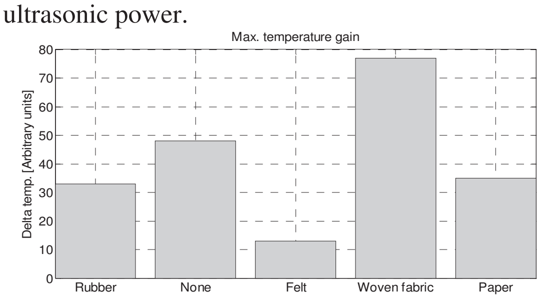

Fig. 10. Differences in thermal response for different coupling materials

5. CONCLUSIONS

Designed prototype measurement system for vibrothermographic testing has been verified to be fully functional. Preliminary testing has been performed on a composite specimen in order to analyze measurement parameters that have the largest influence on measurement results. Contact pressure between the sonotrode and the test specimen has been identified as one of the most important measurement parameters apart from the power of ultrasonic converter, measurement time and coupling material that is used. Further experimentation is necessary to identify the effects of different coupling materials in more detail and ultimately to identify optimal measurement parameters for given structures.

Vibrothermography has a great potential of application in many industrial and research applications, which has been verified experimentally by the authors. The configuration of measurement system is flexible and can be fairly easily adapted to a specific application. Main fields of application of the method, as identified from performed experiments and from literature survey, is the detection of:

- cracks in metallic and composite materials;
- delaminations in composite materials;
- defects in welded joints,
- loose rivets and bolted connections.

The main practical advantages of vibrothermography are:

- nondestructive and noncontact testing procedure;
- short measurement time (typically only few seconds are enough to obtain satisfactory results);
- detection, localization and size of the defect can be evaluated from thermal image processing;
- ease of interpretation of the results.

6. ACKNOWLEDGMENTS

The work on vibrothermography was financed from the research project MONIT - „Monitoring of Technical State of Construction and Evaluation of its Lifespan" (no. POIG.01.01.02-00-013/08-00) made in the scope of the European Union Operational Programme - Innovative Economy 2007-2013

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