THE INFLUENCE OF EXCITATION FREQUENCY ON THE EFFECTIVENESS OF VIBROTHERMOGRAPHIC TESTING

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Summary

The paper investigates the influence of excitation frequency on the effectiveness of vibrothermographic testing. Vibrothermography is a nondestructive testing method that monitors heat produced by damage under vibrational excitation in order to evaluate the structural health. Layered carbon fiber reinforced polymer plate with polytetrafluoroethylene (PTFE) insert, simulating delamination, was analyzed for a range of excitation frequencies. It was found that some of the frequencies generate much higher thermal response from the simulated delamination and should be therefore preferable for vibrothermographic testing. The paper contains the description of the experimental procedure together with presentation and discussion of the results.

Keywords: thermography, vibrothermography, damage detection, laminated composites.

WPŁYW CZĘSTOTLIWOŚCI WYMUSZENIA NA WYNIKI POMIARÓW METODĄ WIBROTERMOGRAFII

Streszczenie

W artykule przeanalizowano eksperymentalnie wpływ częstotliwości wymuszenia na wyniki pomiarów metodą wibrotermografii. Wibrotermografia jest metodą badań nieniszczących która bazuje na pomiarze zmian temperatury pod wpływem wymuszenia drganiowego w celu wykrycia uszkodzeń w badanym materiale. W niniejszej pracy analizie poddano warstwową płytę kompozytową zbrojoną włóknem węglowym w której zasymulowano uszkodzenie w postaci delaminacji. Uszkodzenie zasymulowano przez umieszczenie w płycie wkładki z politetrafluoroetylenu (PTFE). Płytę poddano wymuszeniu drganiowemu w pewnym zakresie częstotliwości i zaobserwowano iż pewne częstotliwości generują znacznie wyższą odpowiedź termiczną w uszkodzonym obszarze płyty niż inne i są przez to preferowane w badaniach wibrotermograficznych. Artykuł zawiera szczegółowy opis metody pomiarowej oraz przeprowadzonych badań eksperymentalnych.

Słowa kluczowe: termografia, wibrotermografia,detekcja uszkodzeń, laminaty kompozytowe.

1. INTRODUCTION

Thermographic nondestructive testing (TNDT) refers to a family of nondestructive testing methodsbased on temperature measurements aimed at revealing structural damage[1]. The measurement techniques analyze the dynamic temperature distribution on a surface of tested objectas a result of applied excitation. The family of active TNDT testing techniques can be classified into two sub categories according to the applied excitation source. The first group comprises the methods utilizing external excitation: flash lamps, infrared lamps or lasers [1,2,3]. The second group comprises methods utilizing internal vibration excitation and inductive heating sources [1,4-6]. The methods from both groups, including pulsed thermography, lock-in thermography and vibrothermography, has been successfully applied in nondestructive testing applications in many fields including: aerospace, automotive, civil engineering or renewable energy among others [1,2,4,7,8].Theincreasing interest in TNDTapplications is due to several factors including the wider availability of affordable thermographic cameras, noncontact nature of the measurement, full field evaluation, short measurement time and simple test setup.

Of particular interest within the group of TNDT methods is, due to its high efficiency, vibrothermography. The method has been already proven very effective in application to damage detection in metallic, composite and ceramic structures. There are, however, a few open questions that should be addresses before the application of vibrothermography in engineering environment [9-11]. One of them is the sensitivity of heat generation on defect to the excitation frequency. It has been already discussed in the scientific literature that there is an influence of the excitation frequency on the amount of heat dissipated at defects [12-15]. This paper presents a detailed study on the frequency related heat generation in a laminated carbon fiber reinforced polymer (CFRP) plate.

The paper is organized in the following way: in paragraph 2 the vibrothermography isdescribed considering both theoretical and experimental aspects of the technique. Paragraph 3 gives the details a laminated carbon fiber reinforced polymer (CFRP) plate that was used as a test case. Paragraph 4 presents the vibrothermographic frequency sweep test that was used to analyze the dependency of thermal response of the plate to the excitation frequency. Paragraph 5 describes theresults of a vibration test performed on the plate with use of a non-contact scanning laser Doppler vibrometer (SLDV) measurements. Paragraph 6 compares the results of vibrothermographic tests performed on the plate for two different modal frequencies. Finally, the summary and conclusionsdrawn from the investigations are presented in paragraph 7.

2. VIBROTHERMOGRAPHY

Vibrothermography is an active TNDT methodthat uses vibration excitationfor the local heat generation. Elastic waves propagating in the material interact with defects such as cracks or delaminations. Due to this interaction the mechanical energy is dissipated into heat. There are several physical mechanisms responsible for this conversion [10, 11] but in many cases the dominating mechanism is friction. Generated heat propagates to the surface, where it may be detected by an infrared camera.Vibrothermography is a defect selective dark field method as heat is generated selectively at the locations of damage. The original research on vibrothermography was done by Hennecke et al. [5] and popularized by Favro et. al. [6]. The experimental setup for vibrothermography is shown in Figure 1. The setup consists of four major components, namely: a vibration source, an infrared camera, a control unit and a computer with dedicated data processing software.

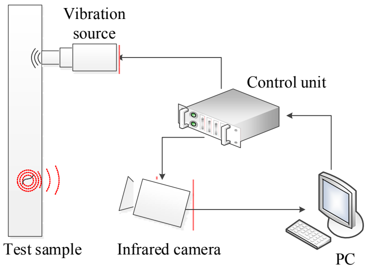


Fig. 1. Test setup of vibrothermography [4]

Currently, the most popular setup for vibration excitation is a narrowband vibration source in the ultrasonic frequency range from 15 to 70 kHz.This type of excitation is typically applied by an ultrasonic device in configuration that is typical for ultrasonic welders, as shown in Figure 2.The device comprises three elements: (1) Langevin type ultrasonic converter to generate vibrations; (2) booster and (3) sonotrode to amplify and deliver the vibration to a structure. This configuration allows high power and narrowband frequency operation. The main drawback of this setup is that the three components (converter, boosted and sonotrode) are designed for a specific working frequency. It is therefore not possible to change the excitation frequency for a given welder setup.

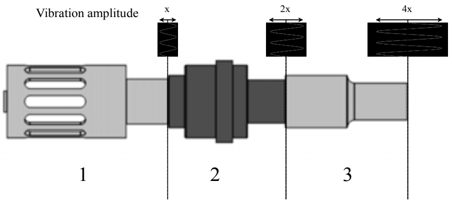


Fig. 2. Ultrasonic welding setup typically used as excitation source in vibrothermography [4]

It has been reported in the scientific literature that the narrowband frequency excitation is not an optimal choice for vibrothermographic measurements [12-15]. The reason is that the measured thermal response on damage is influenced by the excitation frequency. To overcome this problem in the typical ultrasonic welder setup Han et. al. [12-13] proposed the use of a nonlinear coupling, between the sonotrode tip and the tested object, that causes a hammering effect and enriches the frequency spectrum of the excitation. The problem with this solution is, however, the lack of repeatability of excitation, which in this case is nonlinear and potentially chaotic. Holland [14] showed that it is possible to use a piezoelectric stack actuator driven by a chirp signal to obtain a broadband excitation spectrum for vibrothermographic measurements. It has been also observed that defects at different locations produced greater thermal responses at specific excitation frequencies. The main issue of concern in this case is, however, the amount of energy that can be delivered to the measured object. The ultrasonic welder design is meant for high amplitude operation, which is hard to achieve with a piezoelectric stack without the additional wave guide. Montanini et. al. [15] presented a preliminary study on the influence of the excitation frequency on the effectiveness of vibrothermographic test for a steel plate with a set of flat bottom holes filled with viscous material. They have observed that the amount of heat generated at different defects depends on the mode shape that was excited.

In this study the link between the excitation frequency and thermal response of defect is analyzed for a laminated composite plate with artificial delamination.

3. TESTED SPECIMEN

The test specimen was a laminated composite plate made of carbon epoxy prepreg 950-GF3-5H-1000 with the $[0/45_2/0]$ ply sequence. The dimensions of the plate were 588×200×1.2 mm, as shown in Figure 3. The plate contained a seeded delamination made by placing a circular polytetrafluoroethylene (PTFE)insert between second and third plies prior to autoclaving. The center of the insert was located 150 mm from the shorter edge and 100 mm from longer edge of the plate and its diameter was 60 mm.

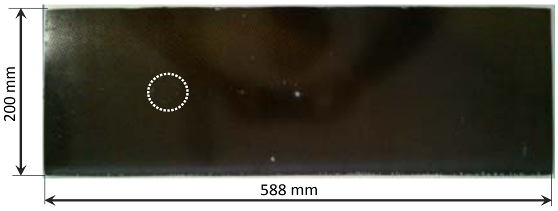


Fig. 3. Dimensions of the test specimen. White circle indicates the location of a PTFE insert

Nondestructive testing by ultrasonic C-Scan method was performed on the sample to confirm the presence and location of the artificial delamination. The C-Scan image of the test specimen, shown in Figure 4,clearly shows the area with no adhesion between plies as blue circle in the left hand side of the plate.

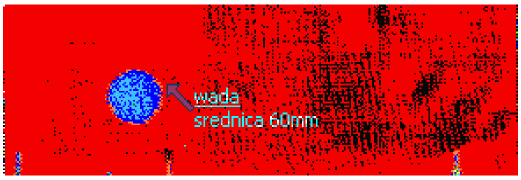


Fig. 4. Ultrasonic C-Scan image of the analyzed composite plate with delamination

4. VIBROTHERMOGRAPHIC FREQUENCY SWEEP TEST

In the first step of the analysis, a vibrothermographic experiment with frequency sweep excitation was performed.The experiment was performed on a laboratory test stand presented schematically in Figure 5. The plate was mounted on a *TMS K2007E01* electromagnetic shaker driven by an *Agilent 33522A* arbitrary waveform generator. A frequency sweep signal was used to excite the plate in the frequency range from 1 Hz to 1000 Hz in the time period of 300 seconds. The surface of the plate was covered with matt black paint to obtain a homogenous surface emissivity close to 1. A photon detector infrared camera*FLIR SILVER 420M* was used to monitor the change of surface temperature on the plate as a result of the applied vibration. The noiseequivalent temperature difference (NETD), that is a measure of sensitivity of an infrared detector, was below 25 mK for thisinfrared camera.The camera was capturing 100 frames per second for the total duration of 300 seconds that was equal to the time of vibrational excitation of the plate.

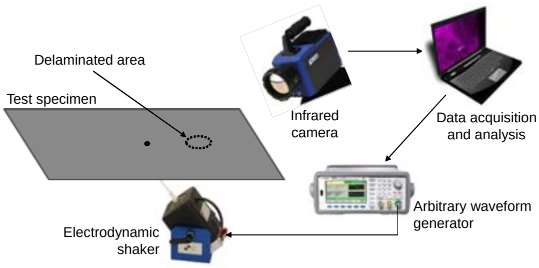


Fig. 5. Laboratory arrangements used for vibrothermographic evaluation of damage

Figure 6 presents the result of the experiment as a time history plot of thechange in surface temperature during the test. The temperature was measured at the location of the delamination. As can be seen there are multiple instances in time when temperature on damage increases rapidly. This is an evidence that there are specific frequencies at which the heat generation rate on damage is significantly higher than in other cases.

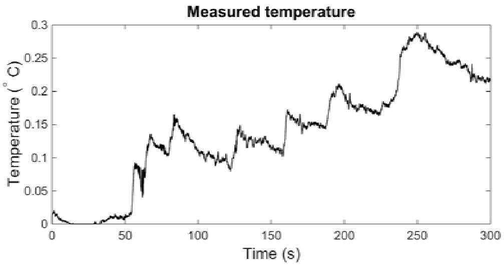


Fig. 6. Evolution of temperature at the location of damage during the frequency sweep test

5. EXPERIMENTAL MODAL ANALYSIS

In order to identify the frequencies and vibration shapes that produce large thermal response observed on damage the experimental modal analysis was performed on the plate. Similarly to the vibrothermographic test the plate was mounted on a *TMS K2007E01* electromagnetic shaker. A white noise signal was used for excitation and *Polytec PSV-400* scanning laser vibrometer was used for non-contact vibration measurements. Vibration responses were acquired from the 30 x 16 mm measurement grid to obtain mode shapes of the plate. The analysis was performed in the frequency range from 0 Hz to 1000 Hz.

There were 26 vibration modes identified in the analyzed frequency range.Based on the analysis of the frequency sweep test two mode shapes at 270 Hz and 300 Hz were selected for further analysis. The mode shape at 270 corresponds to the rapid increase in measured temperature during the frequency sweep test and mode shape at 300 Hz corresponds to the area where no significant temperature change was observed. The locations of both modes are marked by red lines in Figure7.

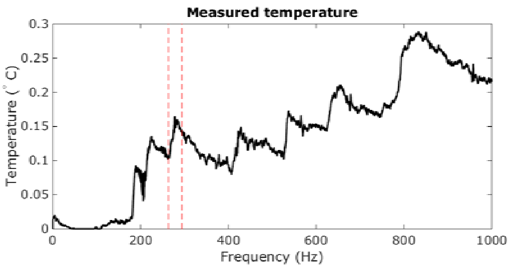
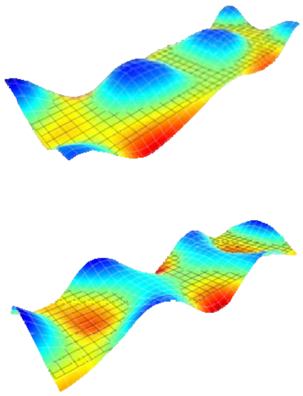


Fig. 7. Evolution of temperature at the location of damage during the frequency sweep test as a function of excitation frequency. Red lines indicate the location of vibration modes selected for further analysis

The mode shapes corresponding to the select excitation frequencies are shown in Figure 8.



(a) 270 Hz

(b) 300 Hz

Fig. 8. Vibration mode shapes selected for vibrothermographic test

6. VIBROTHERMOGRAPHIC TEST

In the last step of the analysis vibrothermographic test was performed on the composite plate with use of the two resonant frequencies identified from the modal test. The same experimental setup was used as in case of the frequency sweep test described in paragraph 2 except from the excitation signals that in this case were a monoharmonic signals at frequencies equal to 270 Hz and 300 Hz respectively. The excitation was applied to the composite plate for 60 seconds, which was also the time for temperature measurement.

Results of this experiment are shown in Figure 9. Two distinct temperature fields were identified for the two analyzed vibration modes, as shown in Figure9a and 9c. First of the analyzed vibration modes at 270 Hz (Figure9a) exhibited strong heating in the area of delamination. This frequency also corresponded to the rapid increase of temperature during the frequency sweep test as shown in Figure 7. The second vibration mode at 300 Hz did not show any significant temperature change in the analyzed area (Figure9c). The relevant temperature values measured at the location of delamination and at the healthy area for the entire test are given in Figure 9b and 9d. Measurement locations are marked on thermographic images in Figure 9a and 9b. Temperature change of 0.12 °C was observed for the 270 Hz vibration mode.

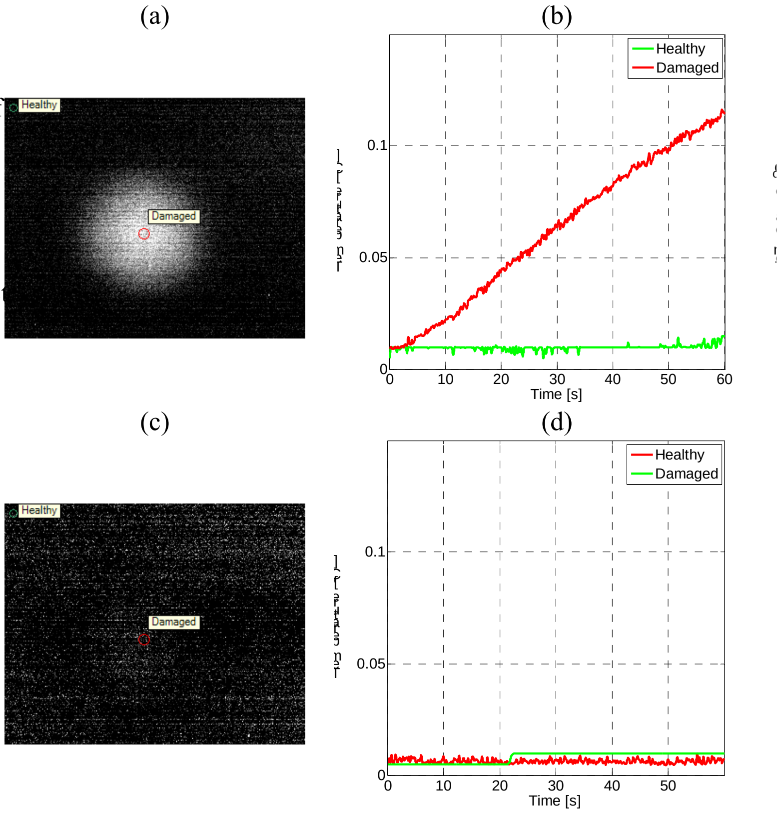


Fig. 9. Thermal response of the artificial delamination for two different excitation frequencies at 270 Hz (a,b) and 300 Hz (c,d)

The same behavior as in case of the excitation at 270 Hz could be observed for other frequencies in the analyzed frequency range where temperature increased rapidly during the vibrothermographic sweep test. The frequencies that were verified to produce large temperature increase at the delamination, in addition to the 270 Hz as described above, are 211 Hz, 407 Hz, 528 Hz, 622 Hz and 750 Hz.

7. SUMMARY AND CONCLUSIONS

The paper presents an experimental study on the influence of the excitation frequency on the amount of heat dissipated on damage during vibrothermographic test. Tests were performed on a laminated carbon fiber reinforced polymer plate with artificial delamination. It has been shown that certain excitation frequencies generate amplified thermal responses of damage and should be therefore preferred for vibrothermographic testing. It is also an indication that the configuration of excitation source (shown in Figure 2) that is currently most widely used is not an optimal choice for vibrothermography. Broadband excitation source should allow for a more efficient heat generation and a tunable excitation source could be used for selective excitation of defects.

Vibrothermography is a very promising TNDT technique that offers short measurement timesand requires relatively simple image processing algorithms, mainly based on the image subtraction methods. There is still a large field for improvement in the design of vibration excitation sources for vibrothermography.

Further investigations are necessary to analyze the dependence of the effectiveness of heat generation on the excitation frequency in more detail.

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