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NON-DESTRUCTIVE TESTING OF COMPOSITE STRUCTURES USING SELF-HEATING BASED VIBROTHERMOGRAPHY AND DEDICATED BENCHMARK

The newly developed self-heating based vibrothermography method is a non-destructive testing method applicable to polymeric and polymer-based composite structures, which is based on the self-heating effect used as thermal excitation of a structure during testing. The mechanical excitation with multiple resonant frequencies causes viscoelastic energy dissipation in the whole structure, which allows the observation of eventual flaws and damage in the form of differences in the surface temperature distribution observed by an infrared camera. The effectiveness of damage detectability depends on the visibility of thermal signatures of potential flaws and damage, which is often masked by measurement noise and artefacts in thermograms. Therefore, it is suitable to apply post-processing procedures that allow the enhancement of damage detectability. The developed set of tools for thermogram post-processing covers primary methods based on statistical features, and more advanced ones like methods based on derivatives, wavelet transform as well as post-processing methods dedicated for thermogram enhancement such as thermographic signal reconstruction, partial least squares regression or principal component thermography. These methods were implemented in the form of an integrated GUI-based benchmark based on Matlab routines, dedicated to the post-processing of thermographic data acquired using self-heating vibrothermography.

Keywords: **self-heating based vibrothermography, non-destructive testing, polymer matrix composites, damage detectability enhancement, benchmark**

BADANIA NIENISZCZĄCE STRUKTUR KOMPOZYTOWYCH Z ZASTOSOWANIEM WIBROTERMOGRAFII OPARTEJ NA SAMOROZGRZANIU ORAZ DEDYKOWANY BENCHMARK

Nowo opracowana metoda wibrotermografii oparta na samorozgrzaniu jest metodą nieniszczącą, którą można stosować do struktur polimerowych oraz do kompozytów o osnowie polimerowej, bazującą na efekcie samorozgrzania stosowanym jako wymuszenie cieplne struktury podczas badań. Wymuszenie mechaniczne na wielu częstotliwościach rezonansowych powoduje lepkosprężystą dyssypację energii w całej strukturze, co pozwala na obserwację ewentualnych wad i uszkodzeń w postaci różnic rozkładu temperatury na powierzchni widocznych za pomocą kamery termograficznej. Efektywność wykrywalności uszkodzeń zależy od widzialności sygnatur cieplnych potencjalnych wad i uszkodzeń, które często są maskowane przez szum pomiarowy i artefakty w termogramach. Dlatego należy stosować procedury przetwarzania, które pozwalają na zwiększenie wykrywalności uszkodzeń. Opracowany zestaw narzędzi do przetwarzania termogramów zawiera metody podstawowe oparte na cechach statystycznych i bardziej zaawansowane, bazujące na pochodnych temperaturowych, transformacji falkowej oraz metodach przetwarzania dedykowanych dla polepszenia jakości termogramów, jak termograficzna rekonstrukcja sygnału, regresja częściowych najmniejszych kwadratów lub termografia głównych składowych. Te metody zostały zaimplementowane w postaci zintegrowanego benchmarku z interfejsem graficznym opartym na algorytmach Matlaba, dedykowanym przetwarzaniu danych termograficznych pozyskanych z zastosowaniem wibrotermografii bazującej na samorozgrzaniu.

Słowa kluczowe: **wibrotermografia bazująca na samorozgrzaniu, badania nieniszczące, kompozyty o osnowie polimerowej, polepszenie wykrywalności uszkodzeń, benchmark**

INTRODUCTION

Due to the growing demands of structural integrity and safety, especially in aircraft and aerospace applications, non-destructive testing (NDT) started to be an inherent element of the maintenance plans and strategies of vehicles, and in particular the structures used in their constructions. Many of these structures are made of polymer-matrix composites (PMCs), which in some cases increase the complexity of inspecting these structures due to material heterogeneity. From the variety of available NDT methods dedicated to PMC structures, the mentioned aircraft and aerospace industries are focused nowadays on non-contact NDT methods [1, 2], which make it possible to inspect structures without their unmounting from vehicles. These NDT methods include primarily optical methods (like digital image correlation or shearography) and thermographic methods with multiple variations, starting from transient thermography and finishing with lock-in thermography and vibrothermography [3]. In most cases, these methods provide fast and full-field measurements, which, besides the high probability of detection and identification accuracy, are high-priority factors which decide about the economical effectiveness of applying these methods.

One of the problems that users of NDT technologies face is the necessity of external excitation of the tested structures, in particular this is the case for the mentioned optical and thermographic methods. The problem appears when direct access to the structure is limited or impossible, and typical excitation methods like applying flash lamps, resistance heaters or lasers [4], are not possible. In order to overcome this problem a new method was developed several years ago [5], namely self-heating vibrothermography (SHVT), which does not require any external thermal excitation since this excitation is provided by mechanical energy dissipation resulting from resonant vibrations of the tested structures. This method of heating is possible due to the thermoviscoelastic behavior of PMCs, and can be successfully applied for diagnostic purposes. In numerous studies [6-10] the capabilities of the SHVT method in detecting, localizing, and identifying various types of damage appearing in PMC structures were demonstrated. It was also demonstrated in [7-9] that applying post-processing of raw thermograms may significantly increase the sensitivity of SHVT to particular types of damage. The tested algorithms include widely used processing methods typical for enhancing thermograms, as well as newly developed methods based on features, derivatives and various transforms. The main goal of this paper is to present the capabilities of the developed benchmark, IRTEnhance (freely available at http://ipkm.polsl.pl/irtenhance), which is a GUI-based application with integrated processing methods and numerous test datasets described in the authors' previous studies cited above. The paper introduces the main concepts of the SHVT method and presents the application of the developed and implemented post-processing methods to enhance thermograms. The developed benchmark can be used for training on real experimental SHVT measurement data, for using this data to develop new signal and image processing methods as well as for exploring the capabilities of the implemented methods in the benchmark.

SELF-HEATING BASED VIBROTHERMOGRAPHY

Self-heating based vibrothermography (SHVT) is a new non-destructive testing method dedicated for detecting and isolating [11] damage that occurs in polymer matrix composite structures. The main idea of SHVT is based on the excitation of a composite structure by applying external mechanical vibrations with resonant frequencies from a low frequency range. Exciting a structure with several resonant frequencies causes heating up of the whole composite structure, which is possible due to the occurrence of the thermoviscoleastic effect called self-heating, whose nature originates from mechanical energy dissipation. If damage occurs in the composite structure heated up by the self-heating effect, then it causes local disturbance in the temperature field which can be detected by measuring the temperature using an IR camera and by applying adequate algorithms of IR image processing. In particular, the developed SHVT approach consists of the following steps [7-9]:

1) identifying the resonant frequencies of the examined structure using experimental modal analysis techniques,
2) generating a multi-harmonic excitation signal, whose components are established by the first few resonant frequencies identified during the modal analysis step,
3) exciting the examined structure by an electrodynamic shaker using the multi-harmonic excitation signal and in consequence heating up the structure by the self-heating effect,
4) measuring the temperature field of the examined structure using an IR camera and registering the thermograms,
5) processing the registered thermograms using adequate IR image analysis algorithms to enhance the detection of damage occurring in the examined structure.

The method described above has been verified in two studies of detecting and localizing various types of damage in PMCs. The raw thermograms obtained during the verification tests as well as the Matlab m-file subroutines of the developed methods of IR image analysis were shared within the IRTEnhance benchmark concerning GUI for users unfamiliar with programming in Matlab.

DAMAGE IDENTIFICATION USING SHVT

Identifying notches and spatial defects

First, the SHVT approach was used in order to detect and localize artificial damage in PMC specimens. The specimens were made of a glass E-fabric-reinforced 14-layered epoxy composite material and were cut from a sheet with the thickness of 2.5 mm into strips with the length of 250 mm and the width of 10 mm. Specific information on the components and the manufacturing process of the described specimens can be found in [12]. To investigate the defect detectability efficiency, flat bottom holes (FBH) were milled in the specimens according to the schemes presented in Figure 1.

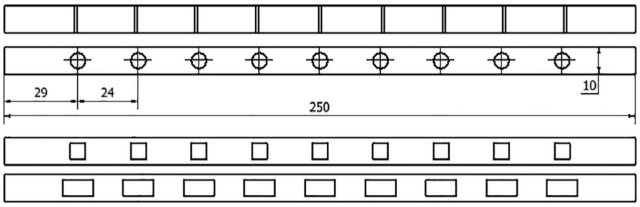

Fig. 1. Diagrams of milled defects with characteristic dimensions of tested specimens [7]

Rys. 1. Schematy wyfrezowanych uszkodzeń z wymiarami badanych próbek [7]

As was shown in Figure 1, four shapes of FBHs were considered: notch-type (L), circular (C), square (S), and rectangular (R). For each defined shape of FBH, six depths were milled, starting from 0.25 mm and ending at 1.5 mm with a step of 0.25 mm, and to ensure appropriate thermal emissivity, the specimens were covered with black matt heat resistant enamel. Following this, 24 specimens in total were prepared and tested using the SHVT approach.

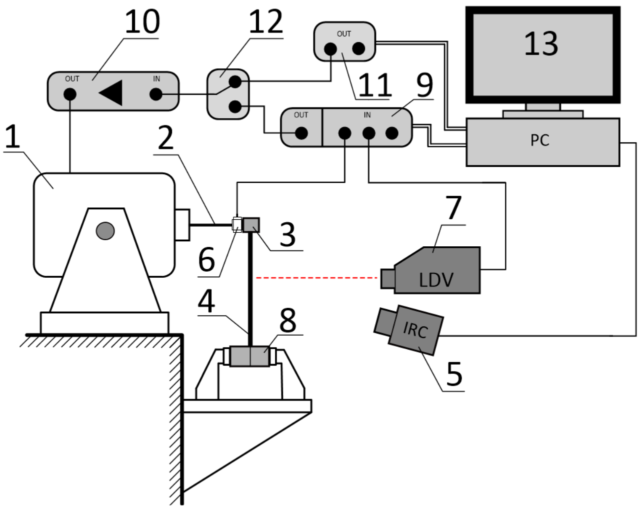

Fig. 2. Diagram of experiment test rig [7]

Rys. 2. Schemat stanowiska badawczego [7]

Due to the construction of the SHVT approach, the testing procedure was divided into two steps:

1) performing classical modal analysis to acquire the resonant frequencies of the tested specimen,
2) excitation of this specimen with a multi-harmonic signal composed of harmonics with acquired resonant frequencies and with simultaneous observation of the top surface of the specimen using the IR camera in order to register its thermal response.

In both steps, the authors' own designed test rig (Fig. 2) was utilized. The test rig consists of an aluminium specimen holder **3** with polycarbonate inserts for thermal insulation, the steel holder **8** on the opposite side of the specimen which is connected through the stinger **2** and the PCB Piezotronics® T352C34 force transducer **6** to the TIRA® TV-51120 electrodynamic shaker **1**. Here the PCB Piezotronics® T352C34 force transducer **6** was used to acquire the reference signal while the TIRA® TV-51120 electrodynamic shaker **1** was applied to load the specimen with a pseudo-random excitation signal, in order to obtain a wide-band frequency response. Vibration measurements and modal analysis were performed using a Polytec® PSV-400, which consists of a scanning laser Doppler vibrometer (LDV) **7**, the Polytec® PSV-W-400 control unit **9** and a PC unit **13** with dedicated software. The excitation signal was generated using this system and amplified by the TIRA® BAA 500 shaker amplifier **10**.

The modal analysis was performed in the frequency range of 0÷1250 Hz with 3200 data points. The vibration was measured at 45 equidistant measurement points, which were defined on the specimen surface across its length by means of the PSV equipment and software functionality. The tested specimens were set to take measurements on the undamaged surface, which was covered with reflective tape to enhance the reflection ability of the LDV laser beam. Based on the acquired frequency response functions (FRFs), the first three resonant bending frequencies with corresponding mode shapes were identified for every specimen.

In the second step, a given specimen was excited simultaneously by three resonant frequencies, which were identified during the modal analysis step. Specimen excitation was conducted by applying the multiharmonic signal which was composed of harmonics based on the identified resonant frequencies. The excitation signal was generated from the authors' own application developed in the National Instruments™ LabView environment. After turning on the switch **12**, the excitation signal was delivered to the TIRA® TV-51120 electrodynamic shaker **1** through a National Instruments™ cDAQ-9174 compact DAQ chassis with a 4-channel ±10 V 16-bit analogue output module NI-9263 **11**. The thermal response of the specimen was registered by an InfraTec VarioCam® hr IR camera **5** with the sampling rate of 2 frames per second. The test duration was set at 5 min, and, in consequence, 600 thermograms were acquired for each specimen.

In the considered study, the analysis of the collected raw thermograms for various types of FBHs revealed that only notch-type FBHs can be directly identified using the SHVT approach. For other types of FBHs i.e. circular, square and rectangular, their thermal signatures were not sharp enough for clear identification (see [7]). In order to enhance the damage detectability, the thermograms acquired during the tests were processed using a procedure consisting of three operations [7]:

1) identifying the time period with effective activity of the self-heating phenomena,
2) adding up the matrices representing the registered thermograms within the previously identified effective time window of self-heating activity,
3) taking the logarithm of the resulting matrix.

The results from this study are available in the developed benchmark through the *Benchmark problems* tab as the set *Milled flat bottom holes*.

Identifying low-velocity impact damage

The second study of the effectiveness of the SHVT approach was focused on detecting and identifying low-velocity impact damage (LVID) in polymer matrix composite (PMC) structures. The specimen dimensions, specimen material properties, test rig composition and testing procedure for SHVT were the same as in the study of identifying notches and spatial defects.

LVID were introduced into the specimens using the authors' own-designed drop weight impact test machine with four impactors: three hemispherical with various radii and one bullet-shaped with a sharp end (see [9] for more details). For each impactor, the range of impact energy values was established by means of the observed effects of the impacts. In particular lower energy values were assumed as the values for which initial damage signatures start to be visible with the naked eye, while the upper energy values were the maximal values at which the specimen was not yet broken. In consequence, 17 specimens with unique LVID were obtained. All the specimens were impacted three times in different locations with the same settings of the drop weight impact test machine. The first impact was in the middle of the specimen, while the other two impacts were located at a distance of approximately 50 mm from the first one in both directions. After preparing the specimens they were covered with black matt heat resistant enamel and tested using the authors' own-designed test rig (see Fig. 2) and the SHVT procedure, both of which were described in previous sections.

The results from this study are available in the developed benchmark through the *Benchmark problems* tab as the set *Low-velocity impact damage*.

Methods of enhancing damage detectability

The analysis of raw thermograms obtained during the SHVT inspection of composite structures may not be effective in many cases of damage detection and localization. This is influenced by various factors disturbing the heat flow generated by the self-heating effect. Among others, one of the factors is thermal diffusion between hot spots which indicate damage and other areas of the examined structure. This results in blurring of the damage signatures in thermograms, and in consequence, difficult identification of damage and reduced sensitivity of SHVT. To overcome this problem several different methods of enhancing thermal images were investigated and applied for enhancement [8, 9]. Special attention was paid to methods of thermogram sequence analysis. In the conducted studies, two groups of such methods were considered, i.e. methods based on statistical features as well as methods based on advanced techniques of IR image analysis.

The application of statistical features is a relatively simple approach of IR image enhancement. In many cases it gives very promising results and allows improvement of the visibility of existing abnormalities in an IR image. Assuming the vector of temperature values $\boldsymbol{a}_i$ over time t, the following statistical features were considered [9]:

- the minimum and maximum value of a_i,
- the mean value, median, variance and standard deviation of a_i,
- peak-to-peak, which is the difference between the maximum and minimum value of a_i,
- the mean and median absolute deviation of a_i,
- the central moment of order k of a_i,
- skewness, which measures the asymmetry of a_i around the mean,
- kurtosis, which measures the "tailedness" of a_i distribution,
- the root-mean-square (RMS) level and root-sum-square (RSS) level of a_i,
- the crest factor, which is the ratio of the largest absolute value to the RMS value of a_i.

Precise definitions of the statistical features listed above can be found in [9].

In the case of the group of advanced methods to enhance damage detectability in an IR image, derivative-based methods, principal component thermography, the non-decimated wavelet transform, partial least-squares regression and thermographic signal reconstruction methods were considered.

The derivative-based approach is useful to emphasize barely visible damage signatures in IR images. In this approach three formulations can be applied to analyse IR images. The first one is the gradient formulation where the directional gradient vectors of the temperature fields of 2D image **A** and their sum are calculated, the second one is the Laplacian which is a differential operator given by a sum of second partial derivatives of **A** with respect to the x and y coordinates, and the third formulation is the Hessian matrix which is the Jacobian of partial derivatives with respect to the x, y coordinates of 2D image **A**.

Principal component thermography (PCT) is another approach used to enhance damage detectability in IR images. The method is based on principal component analysis (PCA), which is a linear projection technique used to convert a set of observations of variables into a set of values of linearly uncorrelated variables, called principal components. In PCT, every single 2D IR image from the ordered sequence is unfolded into the 1D vector and connected together, forming in this way the **A** array, whose columns contain the temperature values over time for each pixel. Next, the **A** array is decomposed on three matrices using SVD decomposition i.e. the **U** matrix representing a set of empirical orthogonal functions describing spatial variation, the **R** diagonal matrix of the singular values and the $\mathbf{V}^T$ transposed matrix representing the characteristic time. Taking into account the resulting matrices from the SVD decomposition, the main idea of PCT is mapping original data from **A** to a new space using the few first large singular values from the **R** matrix and their singular vectors from the **U** and $\mathbf{V}^T$ matrices. The final result of the PCT analysis is obtained after converting transformed matrix **A** back to the original size of the IR image.

The next processing algorithm considered to enhance IR images was the non-decimated discrete wavelet transform (NDWT), which is redundant with respect to classical discrete wavelet transform, however, due to the lack of decimation, the resulting image after transformation has the same dimensions as the input one. NDWT was considered as a single-level decomposition with various wavelets, which is able to enhance the visibility of damage signatures by applying a set of low- and high-pass filters. After decomposition, only the results of high-pass filtering were considered (the detail coefficients), which contain information about damage presence and location.

Partial least-squared regression (PLSR) is an advanced method for image analysis based on the decomposition of predictor matrix **X** and predicted matrix **Y** into loading, scores and residual matrices. In the case of IR image analysis, matrix **X** corresponds to the surface temperature data obtained during the acquisition, matrix **Y** is defined by the time of acquisition and loading matrix **p** computed for predictor **X** represents the new thermal sequence with separated physical effects i.e. damage signatures. The above listed matrices are computed using the nonlinear iterative partial least squares (NIPALS) algorithm.

The last advanced method for enhancing damage detectability in an IR image is the thermographic signal reconstruction (TSR) method. The idea of this method is based on approximating temperature difference ΔT for each pixel by the logarithmic polynomial of degree n with respect to time t. In consequence, the original sequence of temperature rise for each pixel is replaced by n+1 polynomial coefficients. The obtained polynomials are then used to calculate the first and second logarithmic derivatives of the thermograms. This operation allows high-frequency noise to be decreased, the temporal and spatial resolution in IR images to be increased and as well as damage signatures to be emphasized. In this method, proper selection of polynomial degree n is crucial for successful enhancement.

All the applied and above-presented methods were implemented in the developed benchmark.

BENCHMARK

Over the last few years, a great deal of effort has been made in order to develop algorithms for image analysis in the field of the structural damage identification (SDI) of composite materials. Finally, a benchmark containing the developed algorithms and thermographic images obtained from various vibration tests performed during conducted studies was developed. The intention behind the benchmark was to share experimental data and implemented routines among a wide community of researchers in order to develop and test new algorithms for detecting and identifying damage in PMC structures. The benchmark acronym was established as IRTenhance, and it has been openly shared on the benchmark homepage: http://ipkm.polsl.pl/irtenhance. The benchmark contains 41 example problems of 2D damaged composite structures, which are based on experimental data and it as well as allows users to upload their own data. There are example problems of 2D composite specimens with various damage types such as transversal notches and spatial defects like milled rectangular, square and circle holes with different depths. Damage caused by low-velocity impacts are available as well. Both types of considered damage cases are described in separate papers listed on the benchmark homepage. The benchmark was implemented in the Matlab environment as a GUI (Graphical User Interface) application and distributed in the form of both Matlab routines and a stand-alone application, which does not require the Matlab environment to launch and process IR images. Some of the implemented algorithms use routines from the Matlab Wavelet Toolbox and the Image Processing Toolbox, which means that those toolboxes should be available for those who use the source version of the benchmark. Moreover, to make the benchmark available to a wide community, it was fully automated, which means that no programming is necessary to use it.

The IRTenhance benchmark user interface (see Fig. 3) has been divided into three panels: the *Main frame*, *Visualization properties* and *Tools & properties*. The *Main frame* panel is the area where the sequences of thermograms registered during tests (the graph on the left side) and the results of processing of these thermograms using the implemented image analysis algorithms (the graph on the right side) are displayed. The functionality of the *Main frame* panel allows loaded sequences of the thermograms to be viewed. After pressing the *Undock* button, a user can display currently presented images (data image or result image) in a separate window, within which he can edit and save the image in one of the available raster file formats. Another panel, i.e. the *Visualization properties* panel, allows the parameters of images displayed in the *Main frame* panel to be controlled within the range of changing the type of presented graphs, color maps and number of colors as well as image brightness. The last panel, *Tools & properties*, has been divided into four subpanels. These subpanels support analysis of the loaded sequence of thermograms using the implemented algorithms. In particular, the *Data selection* subpanel allowsthe range of the considered sequence of thermograms to be selected based on the graph of the maximum temperature variation and by using two horizontal sliders. The selected range of thermograms is identified on the temperature graph by means of two vertical lines, i.e. the blue and the red line. The blue line determines the low limit of the range, while the red line determines the upper limit of the range. The next subpanel *Data analysis* contains elements to select available image analysis algorithms. Two groups of image analysis algorithms are available i.e. algorithms based on simple statistical features (primary methods) and algorithms based on advanced methods. The group of primary methods includes algorithms to estimate statistical features such as the mean value, standard deviation, root mean squared level and others. In turn, the group of advanced methods includes algorithms, e.g. principal component thermography, thermal signal reconstruction and the non-decimated wavelet transform. Depending on the chosen method, the *Data analysis* subpanel provides additional text edit components and/or popup menus to indicate adequate input parameter values. The last *Post-processing* subpanel contains tools to enhance the obtained results of calculations using power or natural logarithm functions.

surface temperature distribution, which can be observed by an IR camera. The effectiveness of damage detectability depends on the visibility of thermal signatures of potential flaws and damage, which is often masked by measurement noise and artefacts in thermograms. Therefore, it is suitable to apply post-processing procedures that allow damage detectability to be enhanced. The problems mentioned above were considered in studies conducted by the authors within the last four years, thus in this article a summary of those studies was provided with short description of a benchmark concerning the acquired data and developed algorithms of IR image analysis. The IRTenhance benchmark was developed and implemented in the Matlab environment. It contains 41 example problems based on experimental data obtained during tests of real PMC structures with artificially introduced damage of various types.

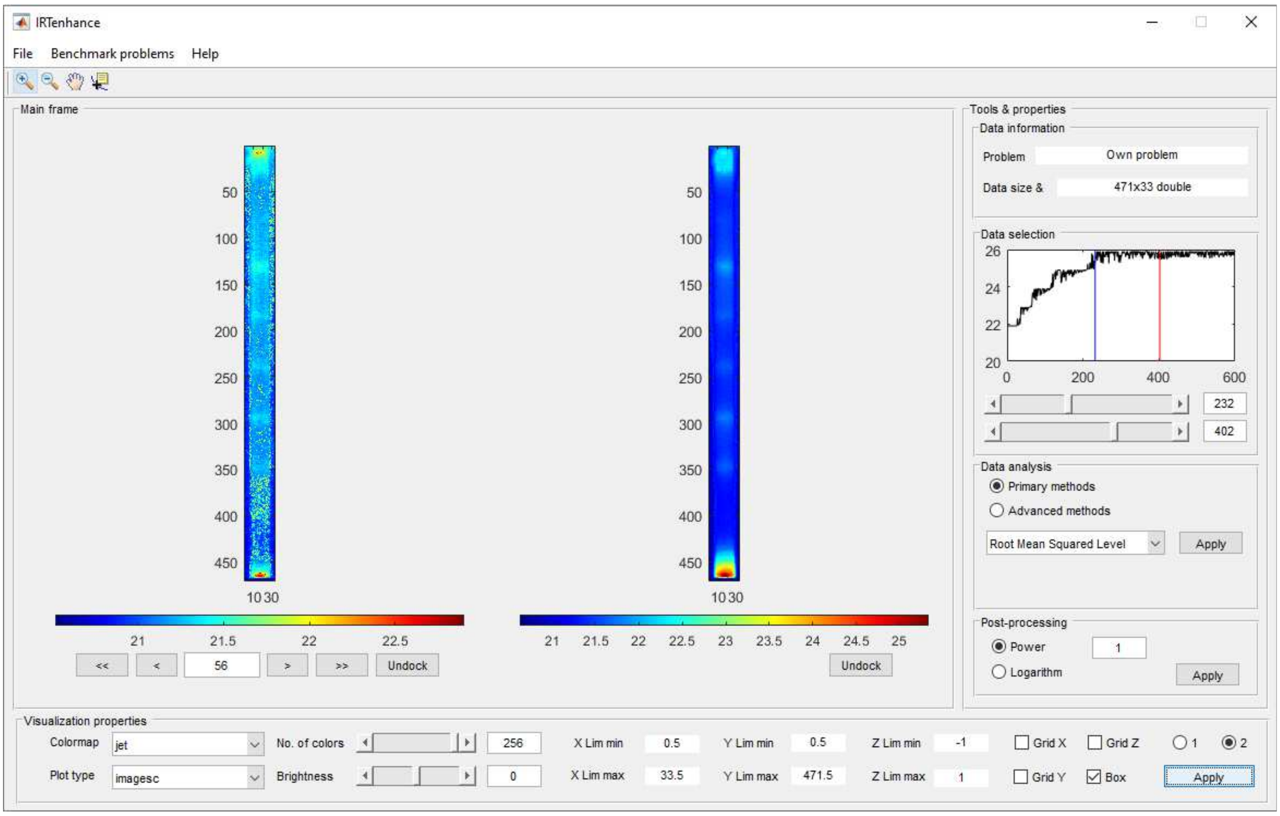

Fig. 3. Graphic user interface (GUI) of IRTEnhance benchmark

Rys. 3. Graficzny interfejs użytkownika aplikacji testowej IRTEnhance

CONCLUSIONS

The newly developed self-heating based vibrothermography method is a non-destructive testing method applicable to polymeric and polymer-based composite structures. It is based on thermal excitation caused by the self-heating effect, which is a result of mechanical excitation of PMCs. The heat flow produced by the self-heating phenomenon allows observation of the eventual flaws and damage in the form of differences in

The benchmark users can use this data to develop and test new algorithms of damage detection and identification. Finally, the benchmark has been developed as a GUI application, which means that coding to perform the analyses is not necessary. In consequence, the process of data analysis is easy and quick, and the benchmark can be used by inexperienced Matlab users. The IRTenhance benchmark is distributed as open-source software (users are able to modify and/or use available code in their own applications), and as a standalone application, which does not require Matlab to be installed on the user's system. The benchmark can be useful for scientists working in the area of nondestructive testing, structural damage assessment, structural health monitoring as well as image processing, in particular IR image processing.

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