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DEVELOPMENT OF *DamageCALC* APPLICATION FOR AUTOMATIC CALCULATION OF THE DAMAGE INDICATOR

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ABSTRACT

This paper presents the development of DamageCALC application for automatic calculation of Damage Detection and Relative Quantification indicator - DRQ. DamageCALC is developed using Visual Basic 6 and enables an automatic graphical interpretation of the damage indicator. The method based on DRQ indicator uses the frequency response functions as the characteristics of the dynamic response of the mechanical system. The DamageCALC automatically reads the measurement results, previously obtained from the modal testing of the beam structure, calculates the value of the corresponding coefficients and forms a chart for the graphical interpretation of the damage indicator values. Following the trend of the calculated DRQ indicators for several successive measurements of the structure, one can determine the existence of a damage of the structure and its propagation.

Keywords: damage indicator, FRF (frequency response function), modal testing, automatic calculation

1. INTRODUCTION

In the most general terms, the structural damage can be defined as changes introduced into a system that adversely affect the current or future performance of that system. Implicitly, in this definition, it is the concept that the damage is not meaningful without a comparison between two different states of the system, one of which is assumed to represent the initial and often undamaged state [1].

The damage may be also defined as any deviation in the structure's original geometric or material properties that may cause undesirable stresses, displacements or vibrations on the structure. These weaknesses and deviations may be due to cracks, loose bolts, broken welds, corrosion, fatigue, etc. All of them should cause a decrease in the structure's stiffness and some will also affect its mass and damping properties.

Therefore, at a sufficient level of severity, the structural damages should always cause a change in a structure's vibration behavior, described by the modal properties: natural frequencies, damping loss factor and mode shapes.

Since the changes of the dynamic characteristics can be measured and studied, it is possible to trace what structural changes have caused the dynamic characteristic to change, thus, identifying the damage [2].

Sampaio and Maia [3] present some new development of the Detection and Relative damage Quantification (DRQ) indicator method, concerning the detection, the localization and the relative severity of the damage. This method belongs to the class of methods using the change in the frequency response functions to detect, locate and relatively quantify the damage. The main advantages of the method are: 1) it is not necessary to perform a modal identification; 2) there is no need for any analytical or numerical model of the structure; 3) it uses all measured data in the form of the frequency response functions, without further treatment. This method is also suitable for an automatic calculation. Therefore, the *DamageCALC* application for an automatic calculation of DRQ indicator and the automatic graphical interpretation of the damage indicator was developed using Visual Basic 6.

2. THEORETICAL DESCRIPTION OF DAMAGE DETECTION METHOD

The Response Vector Assurance Criterion (RVAC) is defined in paper [4] as:

$$RVAC_d(\omega) = \frac{\left| \sum_{i=1}^{N} {}^d\alpha_i(\omega)\,\overline{\alpha_i(\omega)} \right|^2}{\sum_{i=1}^{N}\left[{}^d\alpha_i(\omega)\,\overline{{}^d\alpha_i(\omega)} \right] \sum_{i=1}^{N}\left[\alpha_i(\omega)\,\overline{\alpha_i(\omega)} \right]} \qquad (1)$$

where $\alpha_{ij}(\omega)$ is the element of the system receptance matrix and corresponds to an individual frequency response function, FRF. For only one applied force, the receptance matrix turns to be just a vector, so $\alpha_i(\omega)$ is a single FRF for i-th co-ordinate or measuring point, and N is the total number of measuring points. The element $\alpha_i(\omega)$ corresponds to the undamaged structure, while the superscript d stands for damaged structure.

The Detection and Relative Damage Quantification indicator is formulated in paper [3] as:

$$DRQ_d = \frac{\sum_{\omega} RVAC_d(\omega)}{N_\omega} \qquad (2)$$

where N_ω is the number of frequencies and, thus, DRQ varies between 0 and 1.

The DRQ indicator is able to detect and relatively quantify the damage if the pattern of damage variation is recognized.

3. EXPERIMENTAL INVESTIGATION

In the aim of obtaining the experimental FRFs of the undamaged and damaged structure, the steel beam having the dimensions of 400 mm × 10 mm ×10 mm was modally tested [5]. A crack of 0.5 mm width was introduced by wire-cut. The beam was suspended with common strings to simulate free-free conditions (Fig. 1).

An impact hammer (Endevco type 2230) generated the excitation on each of the 17 nodes uniformly arranged along the beam. An accelerometer (B&K type 4507) was attached to node 5 to capture the vibration signals. The signals were fed into Multi-channel Data Acquisition Unit Portable PULSE (B&K type 3560 C) and analyzed in Labshop 9.0

Pulse software, in the frequency range of 0÷3200 Hz. The modal test was repeated for eight level of damage: *d*=1, 2, 3, corresponding to undamaged beam, *d*=4, 5, 6, 7, 8, corresponding to a crack with the depth of 1÷5 [mm]. The first three natural frequencies for the different damage levels are given in Table 1. Figure 2 shows the overlaid FRFs measured at the 5th measurement location for 8 damage levels. There is some frequency shift due to the increase of the damage that is frequencies move to the left (decrease) due to the decrease of the stiffness of the beam (when damage is increasing). After the calculation of the Response Vector Assurance Criterion (eq. 1) and the Detection and Relative damage Quantification indicator (eq. 2), the results are graphically interpreted as follow in Fig. 3. It is obvious that DRQ indicator shows a decreasing trend as the level of damage is increasing.

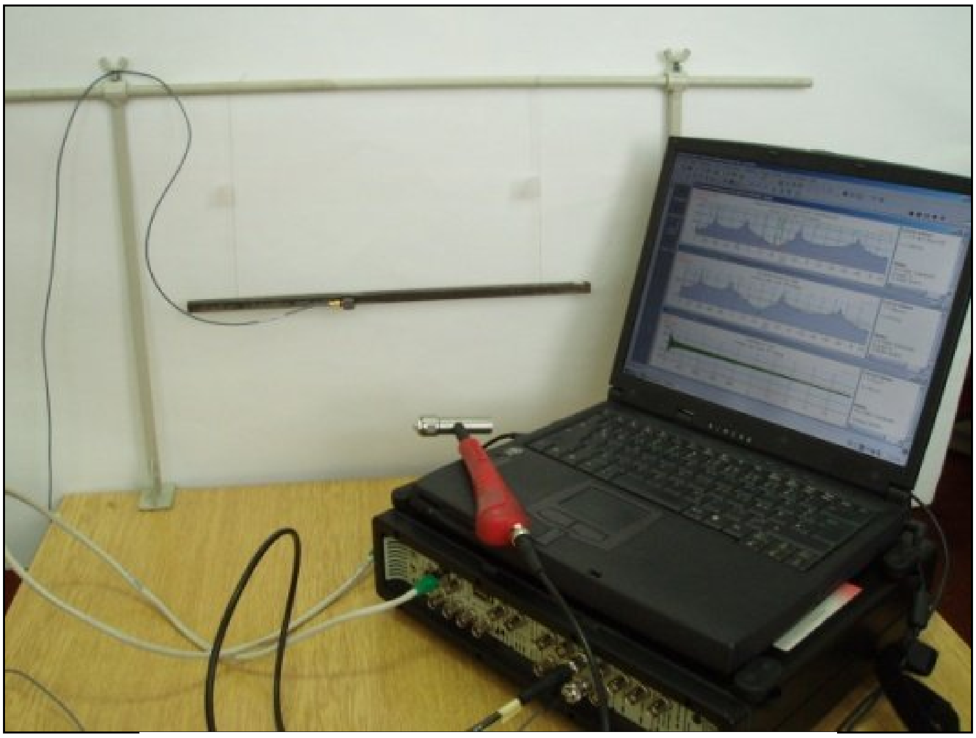


Fig. 1. Freely suspended beam and the equipment used for modal testing

Table 1. Modal frequencies for eight damage levels

	Modal frequencies (Hz)							
	Level of damage "d"							
	1	2	3	4	5	6	7	8
f_1	493			493	493	492	492	491
f_2	1339			1337	1334	1327	1318	1305
f_3	2600			2587	2574	2557	2520	2483

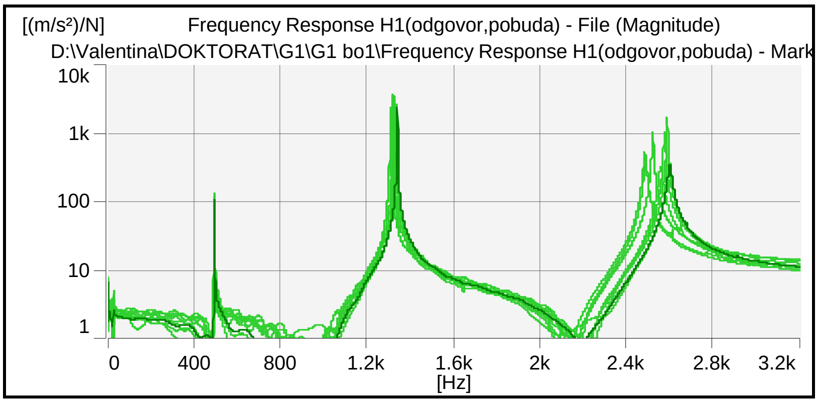


Fig. 2. Overlapped FRFs

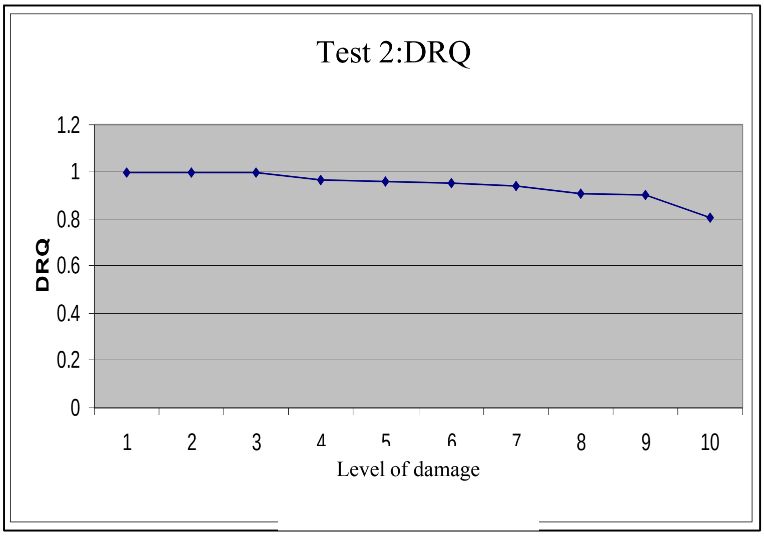


Fig. 3. DRQ recognizes the pattern of damage variation

4. DEVELOPMENT OF *DamageCALC* APPLICATION

Structural health monitoring procedures based on the Detection and Relative damage Quantification (DRQ) indicator method can be done using some automated procedure through the following steps:

1. Measure the FRF at a certain number of locations on the undamaged structure by modal testing.
2. Load FRFs as a text .file into the Damage CALC application.
3. Extract the FRF values for the selected frequencies to calculate the RVAC and DRQ indicators.
4. Start the calculation of RVAC and DRQ indicators.
5. Graphically display the calculated value of the damage indicators.
6. Repeat the entire procedure for each measurement to assess the structural health.

The Detection and Relative damage Quantification indicator method is suitable for automatic calculation. The *DamageCALC* application for the automatic calculation of DRQ indicators and automatic graphical interpretation of results of calculation is developed using Visual Basic 6 [6].

The application automatically reads the measurement results (FRFs) previously obtained by modal testing of the beam structure. After reading the results of measurements, the application calculates the values of the RVAC coefficients for the selected frequency and calculates the DRQ damage indicator for each measurement. Finally, the application designs the graph for a visual interpretation of the measurement results.

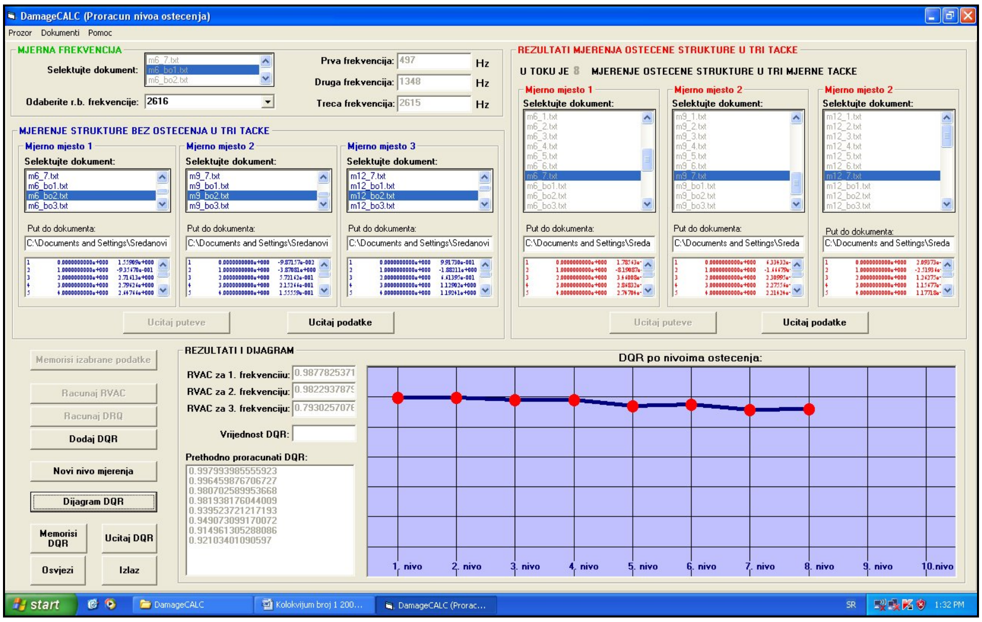


Fig. 4. The developed *DamageCALC* application

For the development of these applications, the standard objects of Visual Basic6th are used. The drop-down menus for the frequency selection, a text fields for input and correction of data and objects for writing and selecting data are placed at the basic form of the application.

The program code of application and objects on the basic form enables the calculation for the ten levels of damage of the structure, for the three measuring points and for three natural frequencies.

It is also possible to memorize the calculated data and to draw diagrams on the basis of the previously memorized information from the damaged structure. The frequency response functions measured in the experiment, as input data for the application, need to be preserved in the form of text documents with .txt extension. The program code of the application finds path to the appropriate text documents and loads them into a working memory of a computer. Developed application *DamageCALC* is shown in Fig. 4.

The application consists of several modules:

1. input frequency module,
2. module for the selection of documents with information on the measurement of the undamaged structure,on about the measurement of the damaged structure,
3. module with the command buttons for the data calculation and memorizing,
4. module for printing the results.

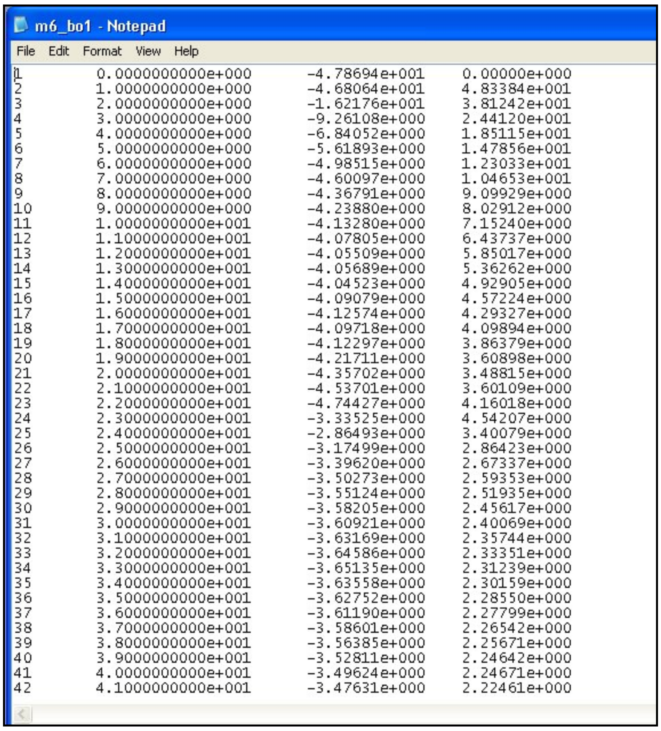
The module (diagram) for the graphical shows the results on a display.

Mechanical Testing and Diagnosis, ISSN 2247 – 9635, 2012 (II), Volume 4, 28-36

4.1. Input Frequency Module

For one measurement, the FRF measured location contains 3200 data that are discrete values of the measured FRF in the range of 0-3200 Hz, with a resolution of 1 Hz (Fig. 5).

For the calculation of RVAC coefficients only three certain frequencies, between 3200 values, are required. Therefore, the application must choose frequencies for which the measured FRF values are read. This is done from the drop-down menu, with pre-selecting any document that contains the measured data (Fig. 6), and the values of selected frequency in [Hz] are automatically printed in the text fields.



m6_bo1 - Notepad

File Edit Format View Help

1	0.0000000000e+000	-4.78694e+001	0.00000e+000
2	1.0000000000e+000	-4.68064e+001	4.83384e+001
3	2.0000000000e+000	-1.62176e+001	3.81242e+001
4	3.0000000000e+000	-9.26108e+000	2.44120e+001
5	4.0000000000e+000	-6.84052e+000	1.85115e+001
6	5.0000000000e+000	-5.61893e+000	1.47856e+001
7	6.0000000000e+000	-4.98515e+000	1.23033e+001
8	7.0000000000e+000	-4.60097e+000	1.04653e+001
9	8.0000000000e+000	-4.36791e+000	9.09929e+000
10	9.0000000000e+000	-4.23880e+000	8.02912e+000
11	1.0000000000e+001	-4.13280e+000	7.15240e+000
12	1.1000000000e+001	-4.07805e+000	6.43737e+000
13	1.2000000000e+001	-4.05509e+000	5.85017e+000
14	1.3000000000e+001	-4.05689e+000	5.36262e+000
15	1.4000000000e+001	-4.04523e+000	4.92905e+000
16	1.5000000000e+001	-4.09079e+000	4.57224e+000
17	1.6000000000e+001	-4.12574e+000	4.29327e+000
18	1.7000000000e+001	-4.09718e+000	4.09894e+000
19	1.8000000000e+001	-4.12297e+000	3.86379e+000
20	1.9000000000e+001	-4.21711e+000	3.60898e+000
21	2.0000000000e+001	-4.35702e+000	3.48815e+000
22	2.1000000000e+001	-4.53701e+000	3.60109e+000
23	2.2000000000e+001	-4.74427e+000	4.16018e+000
24	2.3000000000e+001	-3.33525e+000	4.54207e+000
25	2.4000000000e+001	-2.86493e+000	3.40079e+000
26	2.5000000000e+001	-3.17499e+000	2.86423e+000
27	2.6000000000e+001	-3.39620e+000	2.67337e+000
28	2.7000000000e+001	-3.50273e+000	2.59353e+000
29	2.8000000000e+001	-3.55124e+000	2.51935e+000
30	2.9000000000e+001	-3.58205e+000	2.45617e+000
31	3.0000000000e+001	-3.60921e+000	2.40069e+000
32	3.1000000000e+001	-3.63169e+000	2.35744e+000
33	3.2000000000e+001	-3.64586e+000	2.33351e+000
34	3.3000000000e+001	-3.65135e+000	2.31239e+000
35	3.4000000000e+001	-3.63558e+000	2.30159e+000
36	3.5000000000e+001	-3.62752e+000	2.28550e+000
37	3.6000000000e+001	-3.61190e+000	2.27799e+000
38	3.7000000000e+001	-3.58601e+000	2.26542e+000
39	3.8000000000e+001	-3.56385e+000	2.25671e+000
40	3.9000000000e+001	-3.52811e+000	2.24642e+000
41	4.0000000000e+001	-3.49624e+000	2.24671e+000
42	4.1000000000e+001	-3.47631e+000	2.22461e+000

Fig. 5. Text document with FRF data

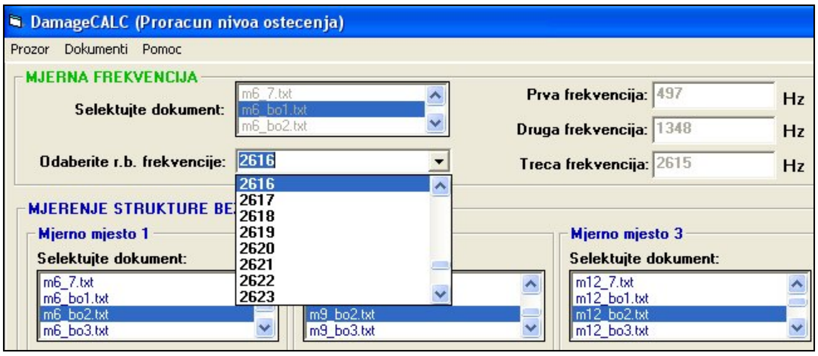


Fig. 6. Drop-down menu for the frequency selection

4.2. Modules for Selectingof the Documents with Information on the Measurement of the Undamaged and Damaged Structure

After selecting the frequency, the documents with FRFs data measured on the undamaged structure in three measurement locations are selected. The path to the selecteddocuments is automatically printed by pressing the button "Loadpaths". Based on the printed path, the data from a given document are listed by pressing the button "LoadData". Loading can be done only if each of the three documents with the data of measurements in three locations is selected.

Especially, a separate module for the selection of documents containing measurement information from the undamaged structure and a module for the selection of documents containing measurement informing on the damaged structures in the three points are separately given Fig. 7.

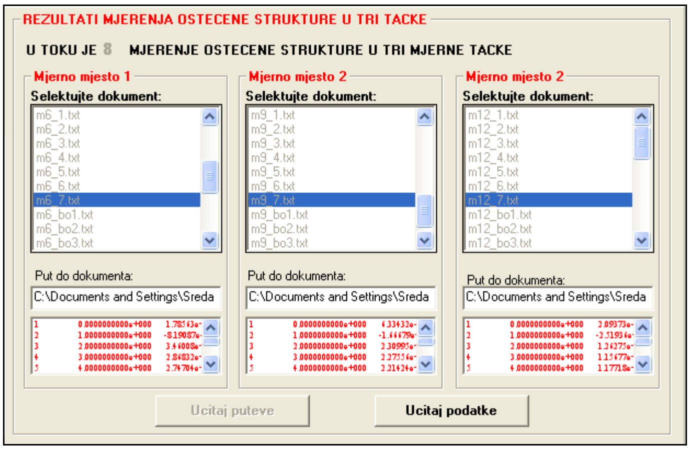


Fig. 7. Fields for selecting the documents containing the measurement data

Fig. 8. The command module of *DamageCALC*

Mechanical Testing and Diagnosis, ISSN 2247 – 9635, 2012 (II), Volume 4, 28-36

4.3. Module with the Command Buttons for the data Calculation and Memorization

The command part of the application consists of a few buttons, (Fig. 8). By pressing the button "Memorize the selected data", the application memorizes the data that are read from the listed documents, namely, those corresponding to the previously selected frequency. After the data are memorized, the coefficient RVAC for each of the three frequencies is calculated. DRQ indicator is calculated on the basis of the previously calculated RVAC values. The button "Add DRQ" writes the calculated data in the appropriate field.

4.4. Modules forPrinting the Results and Graphical Display

The calculated values of DQR indicator can be memorized in a separate document that can be re-loaded into the application and used for a graphical analysis. The entire process of analysis for the next measurement (next level of damage) begins with pushing the button "new level of measurement", where currently memorized data could be deleted and the user gets the possibility to select data documents again.

The output data obtained by calculation are printed in a separate module, Fig. 9. Pressing the button "Diagram DRQ", the application shows the graph of the calculated value of the indicators DRQ.

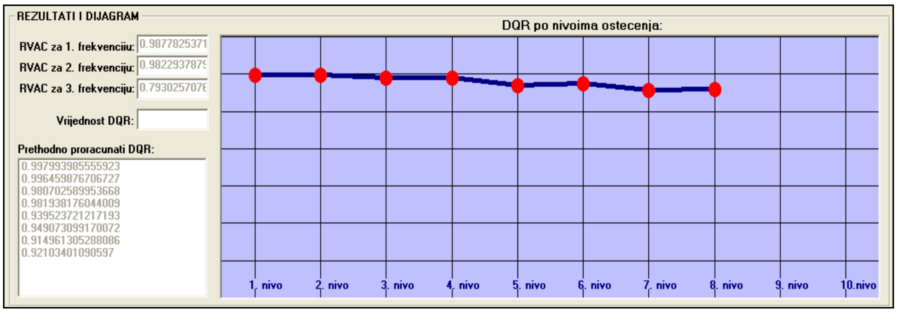


Fig. 9. Module with output data, graphically displayed

5. CONCLUSION

The *DamageCALC* application is developed in a way that all operations are carried out by a simple selection of data and documents, which makes it easy to handle. The application is simple for transferring and requires no installation. The documents containing the measurement data are copied to the folder containing the application, or the application itself is copied into the folder with the corresponding documents.

The structural health monitoring procedures based on the Detection and Relative Damage Quantification (DRQ) indicator method can be done using Damage CALC application through the following steps:

1. Measure the FRF at three locations on the undamaged structure by modal testing.
2. Load FRFs as a text file into the Damage CALCapplication.
3. Extract the FRF values for the selected frequencies to calculate the RVAC and DRQ indicators.
4. Start the calculation of RVAC and DRQ indicators.
5. Graphically display the calculated value of the damage indicators.
6. Repeat the entire procedure for each measurement to assess the structural health.

DRQ indicator is able to detect and relatively quantify the damage, if it recognized the pattern of damage variation. So, one can follow the trend of the change of DRQ indicator by graphically displaying all the calculated DRQ for a series of measurements.

REFERENCES

1. **Farrar C.R., Doebling S.W.,** 1999, Damage detection and evaluation, Modal analysis and Testing, NATO Science series, pp. 345-378.
2. **Yan Y.J. et at.**, 2007, Development in vibration-based structural damage detection technique, *Mechanical system and signal processing* 21, pp. 2198-221.
3. **Sampaio, R.P.C., Maia N.M.M.,** 2008, Strategies for an efficient indicator of structural damage, *Mechanical System and Signal Processing*, vol. 22.
4. **Heylen W., Lammens S.,** 1998, Modal Analysis Theory and Testing. K. U. Leuven-PMA, section A6.
5. **Golubović-Bugarski V. et al.,** 2011, Detection of structural damage location using frequency response function data, *DEMI 2010 Conference*, BanjaLuka, BiH, pp. 50-54.
6. **Golubović-Bugarski V.,** 2010, Models of correlation between structural damages and dynamic response of mechanical system (Modeli korelacije strukturnih oštećenja sa dinamičkim odgovorom mehaničkog sistema), PhD thesis, Faculty of mechanical Engineering, University of Banja Luka.
7. **Maia N.M.M., Silva He J.M.M., Lieven N.A.J., Lin R.M., Skingle G.W., To W.-M., Urgueira A.P.V.,** 1997, Theoretical and experimental modal analysis, Research Studies Press LTD, John-Wiley & Sons Inv. Ewins, D.J.. Ewins, D.