EAN 2017
55th conference on experimental stress analysis

Experimental modal analysis of a free suspended composite plate by using high speed DIC method

Róbert Huňady[1, a] and Peter Pavelka[1, b]

[1]Technical University of Košice, Faculty of Mechanical Engineering, Slovakia

[a]robert.hunady@tuke.sk, [b]peter.pavelka@tuke.sk

Keywords: modal analysis, composite plate, digital image correlation, DICMAN 3D

Abstract. Experimental modal analysis is a measurement method to determine modal parameters of mechanical structures. It can be used as a tool for the verification of numerical models or to identify the mechanical properties of different material specimens. The aim of this paper is to present the possibilities of using the high speed digital image correlation (DIC) in experimental modal analysis. DIC is non-contact optical method, which for the measurement uses precise digital cameras with high image resolution. The main advantage of this approach is that the results are available as full-field data. On the other hand, the FRF matrix resulting from the measurement is usually relatively large; it may consist of thousands of measurement DOFs. Therefore the authors used a special application DICMAN 3D that was developed to evaluate such type of measurements. The experimental results are correlated with the results of FEM analysis.

Introduction

Non-contact optical methods allowing full-field measurements belong to the current trends in experimental mechanics. Into this group scanning laser Doppler vibrometry (SLDV), electronic speckle pattern interferometry (ESPI), digital speckle shearography (DSI), and digital image correlation (DIC) can be incorporated [1, 2]. Digital image correlation is a method which has potential for use in vibration analysis [3], for this purpose it is necessary to use of high-speed cameras. Although the DIC method is mainly utilized for testing of components and determination of material properties [4-7], various contributions devoted to vibration analysis as well as modal analysis are published [8-12].

The conception of the method allows observation of various phenomena during deformation and/or movement of an object, and the method is suitable for testing of a wide range of materials. The fundamental of digital image correlation is based on capturing of a stochastic speckle pattern created on an investigated object surface, e.g., by the spraying of black color on a white background. The use of preprinted vinyl foils is also convenient [7, 8]. An observed region is divided into smaller subsets, so-called facets, in such a way that each of facets includes a characteristic part of speckle pattern with sufficient contrast in order to be ensured its uniqueness. The relative displacements are determined by correlation of corresponding facets in a state before and after deformation of the object, or with regard to a reference step. As the system tracks a wide range of points on the object surface via two cameras, the obtained results are in the form of displacement component fields in directions x, y and z [2]. The principle of DIC is explained in detail in the book [13].

As DIC method measures responses in the form of displacements, frequency response functions (FRFs) are in the form of receptance. The sensibility of the measuring system depends on the resolution of CMOS sensor and size of measured surface. The frequency range is limited by the sampling frequency of cameras, i.e. the reciprocal value of a minimal shutter time. Currently there are high-speed cameras with sampling frequencies from several thousand up to several hundred thousand fps at full resolution of a sensor. If the sensor region of interest is decreased, then the maximal frame rate is increased. Measurements at high frame rates require using of an additional source of illumination for ensuring of optimal light conditions. For that purpose, high-power reflectors with specified achromatic light are commonly used. The major advantage of DIC is an ability to capture the responses of all points on the object surface in the same time and under the same conditions as an excitation. When compared to conventional techniques it means a significant time savings in terms of measurement because it is not necessary to relocate the sensors and repeat the measurement several times. However, it is necessary to note that the correlation is relatively time consuming. The density of measuring points (mesh points) and also accuracy of the measurement is dependent on the facet size. Authors [8] investigated the influence of the facet size on modal parameters estimated from DIC measurement. They found that the facet size has no impact on natural frequencies, however, in the case where the facets are too small, an increase in correlation errors which introduce inaccuracies to frequency response functions occurs. The facet size has a significant influence on absolute amplitudes of mode shapes. Depending on the facet size the amplitudes may be changed in tens of percent.

DICMAN 3D

Since DIC measurement systems usually do not have any software tools for the evaluation of such types of measurement, the use of an external post-processing application is necessary. For that purpose, the authors use a software application called DICMAN 3D [14] that was developed especially for the high-speed digital image correlation system Q-450 Dantec Dynamics.

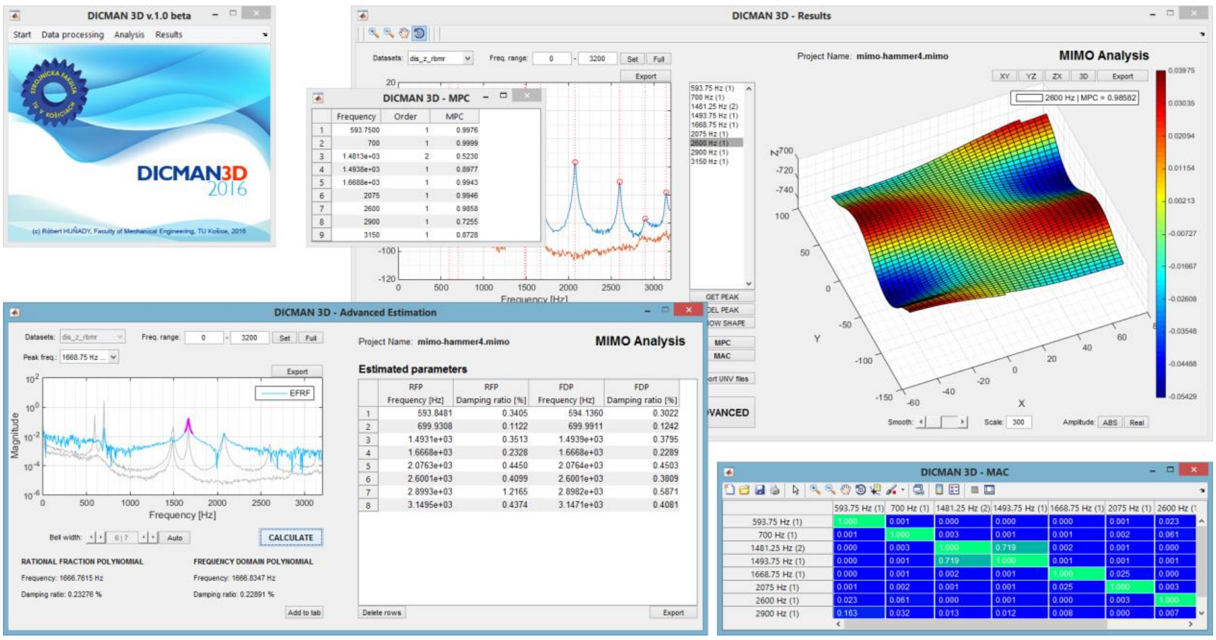


Fig. 1 Graphical user interface of DICMAN 3D.

The system consists of two high-speed cameras, a light source and a powerful notebook with the correlation software Istra4D, which ensures the operation of the measuring device, the cameras calibration and the correlation of images. The measurement is evaluated in Istra4D and the data is saved as HDF5 files. The number of files corresponds to the number of time steps. Each file contains information about the excitation signal and surface point displacements that represent measured responses. The files are subsequently imported to DICMAN 3D. DICMAN 3D has an intuitive graphical user interface (Fig. 1) and is able to evaluate a single-reference as well as a multi-reference measurement. Modal parameters are determined in the frequency domain by means of the following algorithms:

- Complex Mode Indicator Function (CMIF),
- Enhanced Frequency Response Function (EFRF),
- Rational Fraction Polynomial (RFP),
- Frequency Domain Polynomial (FDP).

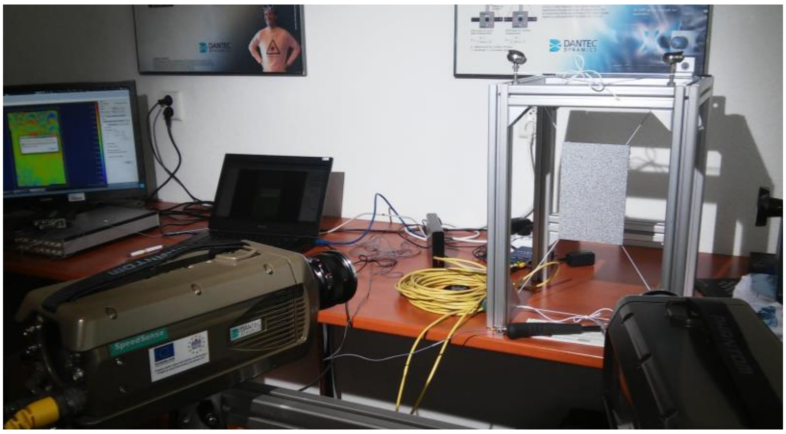
Experimental measurement

The measurement object was a free suspended composite plate of a rectangular shape with the dimensions of 130x200 mm and the thickness of 5 mm. The suspension was realized by 4 elastic bands glued on the rear side of the plate. The plate consists of twenty-five plies with an epoxy matrix. Eighteen of the plies were stiffened by the unidirectional carbon fibers (UCF) and the others by the carbon cross-woven (CCW) with the same volume of warp and weft fibers. An overall composition of the composite plate is shown in Table 1.

Table 1 Ply layup of the composite plate.

Ply	Angle	Reinforc.	Ply	Angle	Reinforc.	Ply	Angle	Reinforc.	Ply	Angle	Reinforc.	Ply	Angle	Reinforc.
1	45°	UCF	**6**	90°	CCW	**11**	-45°	UCF	**16**	-45°	UCF	**21**	-45°	UCF
2	45°	UCF	**7**	45°	UCF	**12**	45°	UCF	**17**	90°	CCW	**22**	-45°	UCF
3	90°	CCW	**8**	45°	UCF	**13**	90°	CCW	**18**	45°	UCF	**23**	90°	CCW
4	-45°	UCF	**9**	90°	CCW	**14**	45°	UCF	**19**	45°	UCF	**24**	45°	UCF
5	-45°	UCF	**10**	-45°	UCF	**15**	-45°	UCF	**20**	90°	CCW	**25**	45°	UCF

The plate was excited by an impact hammer at two different points. The responses were measured by correlation system Q-450 Dantec Dynamics. The frequency range was set to 6400 Hz. Both measurements were correlated in Istra4D software to determine vibration responses, i.e. displacement fields. Time-dependent data were subsequently exported to DICMAN 3D for the estimation of modal parameters. The experimental configuration for the excitation with an impact hammer is shown in Fig. 2.

a) 

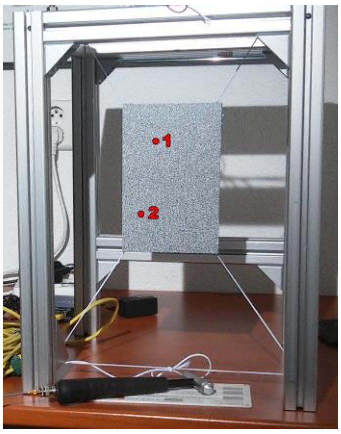
b) 

Fig. 2 a) Configuration of the experiment, b) Excitation points.

Fig. 3 shows the spectrum of CMIF function that was extracted from the FRF matrix by singular value decomposition. As can be seen, seven modes were identified in the given frequency range. Their natural frequencies and damping ratios estimated by RFP method and FDP method are listed in Table 2. The corresponding mode shapes are shown in Fig. 5.

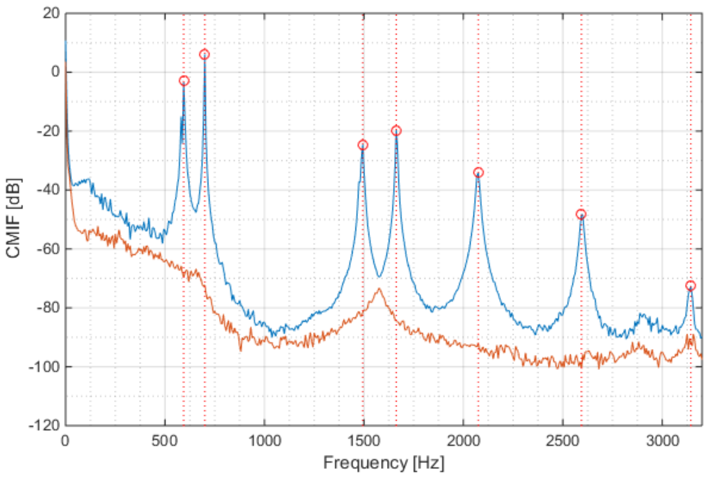


Fig. 3 CMIF plot of the composite plate.

Table 2 Modal parameters of the composite plate determined by DICMAN 3D.

Mode #	**Rational Fraction Polynomial**		**Frequency Domain Polynomial**		**Modal Phase Collinearity**
	Frequency [Hz]	**Damp. ratio [%]**	**Frequency [Hz]**	**Damp. ratio [%]**	
1.	593.89	0.345	594.14	0.295	0.998
2.	699.89	0.119	699.99	0.122	0.999
3.	1492.9	0.362	1494.1	0.401	0.885
4.	1666.7	0.234	1666.8	0.228	0.994
5.	2076.4	0.447	2076.9	0.438	0.994
6.	2600.2	0.419	2600.0	0.382	0.988
7.	3149.9	0.445	3147.6	0.401	0.841

The natural frequencies determined by the RFP method are nearly equal to the frequencies acquired by the FDP method. The differences in the damping ratio values can be considered as acceptable with respect to a different polynomial order of both methods.

FEM analysis of the composite plate

Finite element (FE) model of the composite plate was created in NX Nastran software. The material properties of the final composite were derived from the material properties of phases forming the individual plies. The continuous phase was epoxy resin. The dispersed phases were created by unidirectional carbon fibers UTS-120 and by carbon woven GG-160T (see Table 1). Linear shell elements QUAD4 of 2 mm length were used to mesh the plate. The additional mass representing the layer of used glue was added to every corner of the model (Fig. 4). It provided the better approximation of dynamic behavior the model. The weight of additional masses was determined by the measurement.

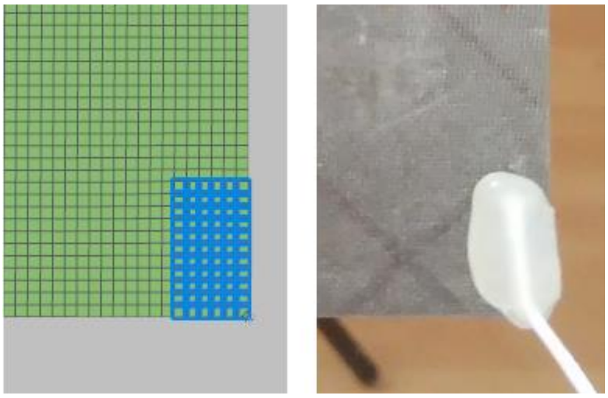


Fig. 4 Additional mass representing the layer of glue.

The eigenvalue analysis was performed in a solver SOL103. There were determined 8 flexible mode shapes of which frequencies are listed in Table 3. The rigid body modes were excluded from the evaluation.

Table 3 Natural frequencies of the composite plate determined by FEM.

Mode #	1	2.	3.	4.	5.	6.	7.	8.
Freq. [Hz]	567.17	677.47	1443.9	1484.0	1595.8	2019.4	2604.8	3119.9

Correlation of the results

It is obvious from Table 3 that one more mode was identified by the FEM analysis. For that reason, the correlation analysis of the results obtained from the experiment and the simulation was performed in NX Nastran. Consistency between the individual mode shapes was determined by Modal Assurance Criterion (MAC). The comparison of the natural frequencies and the mode shapes of the composite plate (Fig. 5) is shown in Table 4.

Table 4 Comparison of modal parameters obtained from the experiment and the simulation.

Mode #	**Natural frequency [Hz]**			**MAC**
	Experiment	**FEM**	**Freq. error [%]**	
1.	593.89	567.17	-4.499	0.784
2.	699.89	677.47	-3.218	0.885
3.	*unidentified*	1443.9	-	-
4.	1492.9	1484.0	-0.596	0.712
5.	1666.7	1595.8	-4.373	0.801
6.	2076.4	2019.4	-2.679	0.879
7.	2600.2	2604.8	0.185	0.826
8.	3149.9	3119.9	-0.955	0.810

As can be seen in Table 4, the frequencies of the third and the fourth mode obtained from the simulation are relatively closed. It is likely that in the case of the real plate these two modes overlap each other. If the excitation is applied at the place of a node point of a given mode shape, this mode is not enough excited. If we compare Fig. 2b with Fig. 5-3 we can see that both excitation points lie near the node curve of the third mode shapes. This is the reason why the responses of this mode were not be measured.

Differences between the natural frequencies are within the range of 0.2% to 4.5%. It is acceptable with respect to uncertainty in boundary conditions and material properties. Consistency of the mode shapes given by MAC value shows also a high level.

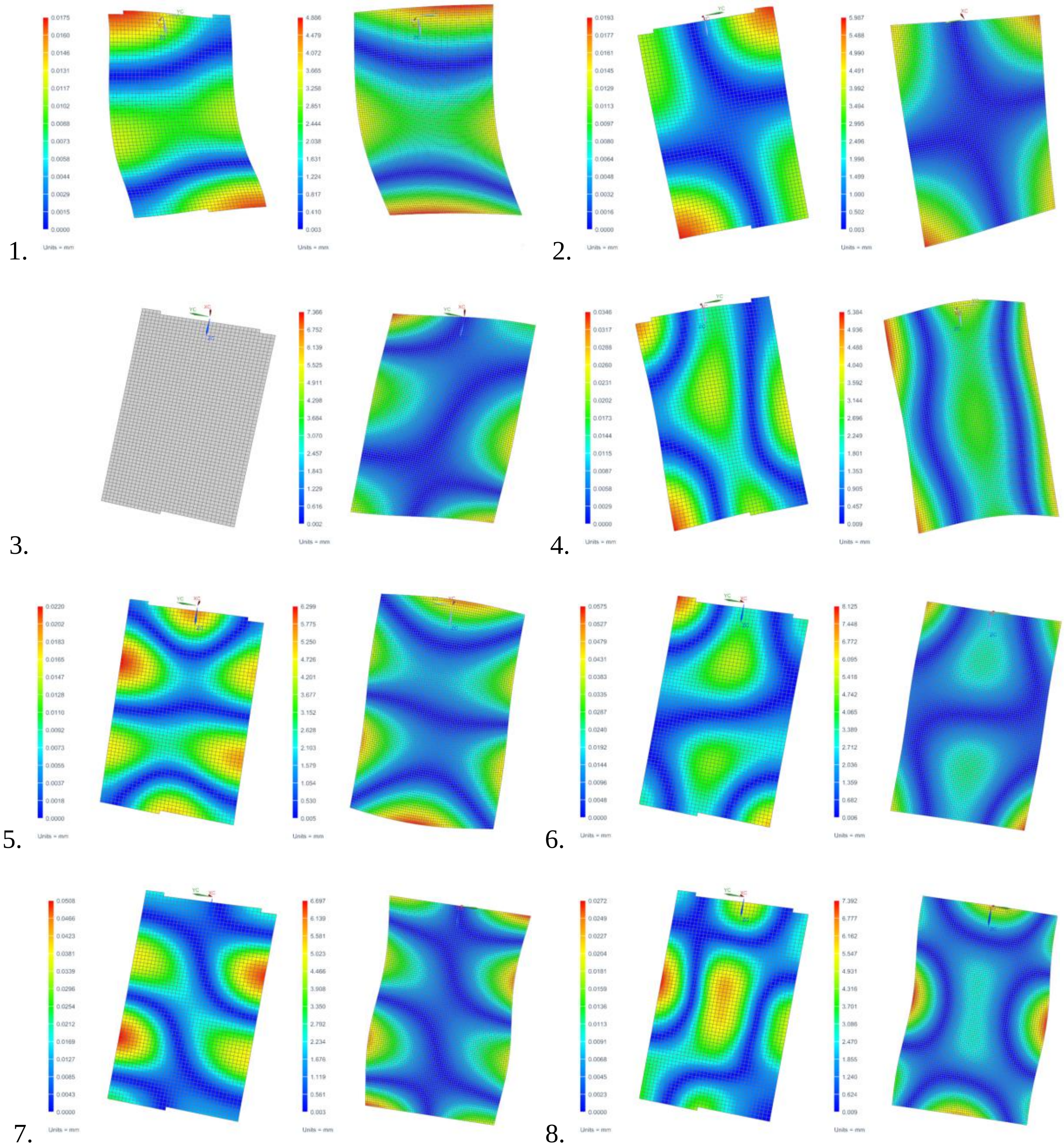


Fig. 5 Mode shapes of the composite plate obtained from the experiment (left) and the FEM simulation (right).

Conclusions

The paper dealt with the use of high-speed digital image correlation in experimental modal analysis. The paper described the modal analysis of the composite plate that was excited by impact hammer. The multi-reference measurement was performed to obtain modal parameters of the plate. The responses were measured by digital image correlation system Q-450. The measurement was evaluated in the software application DICMAN 3D that was created especially for that purpose. The results of experiment are natural frequencies, damping ratios and shapes of the excited modes. Since DICMAN 3D allows to export the geometric model and mode shapes into UNV file format compatible with I-DEAS applications, the experimental results were compared with the results of FEM simulation.

Acknowledgement

The authors would like to express their gratitude to Scientific Grant Agency VEGA MŠ SR for the support of this work under the project no. 1/0751/16 and 1/0393/14.

References

[1] F. Trebuňa, F. Šimčák, P. Frankovský, R. Huňady, M. Pástor, *The Application of Optical Methods in Experimental Mechanics 1* (In Slovak), Technical University of Košice, Košice, 2014.

[2] F. Trebuňa, F. Šimčák, R. Huňady, M. Pástor, P. Frankovský, M. Hagara, *The Application of Optical Methods in Experimental Mechanics 2* (In Slovak), Technical University of Košice, Košice, 2015.

[3] F. Trebuňa, F. Šimčák, R. Huňady, *Vibration and Modal Analysis of Mechanical Systems* (In Slovak), Technical University of Košice, Košice, 2012.

[4] K. Genovese, L. Cortese, M. Rossi, D. Amodio, A 360-deg digital image correlation system for materials testing, *Optics and Lasers in Engineering* 82 (2016) 127-134, http://dx.doi.org/10.1016/j.optlaseng.2016.02.015.

[5] B. Pan, L. Yu, Y. Yang, W. Song, L. Guo, Full-field transient 3D deformation measurement of 3D braided composite panels during ballistic impact using single-camera high-speed stereo-digital image correlation, *Composite Structures* 157 (2016) 25-32, http://dx.doi.org/10.1016/j.compstruct.2016.08.017.

[6] E. Gariboldi, K. Naumenko, O. Ozhoga-Maslovskaja, E. Zappa, Analysis of anisotropic damage in forged Al–Cu–Mg–Si alloy based on creep tests, micrographs of fractured specimen and digital image correlations, *Materials Science and Engineering: A* 652 (2016) 175-185, http://dx.doi.org/10.1016/j.msea.2015.11.090.

[7] R. Huňady, M. Hagara, F. Trebuňa, Stress analysis performed in the near surrounding of small hole by a digital image correlation method, *Acta Mechanica Slovaca* 18 (3-4) (2015) 74–81.

[8] R. Huňady, M. Hagara, F. Šimčák, The influence of facet size on the accuracy of modal parameters determined by digital image correlation technique, *Applied Mechanics and Materials* 611 (2014) 496-500.

[9] N.S. Ha, H.M. Vang, N.S. Goo, Modal analysis using digital image correlation technique: an application to artificial wing mimicking beetle's hind wing, *Experimental Mechanics* 55 (5) (2015) 989–998, http://dx.doi.org/10.1007/s11340-015-9987-2.

[10] W. Wang, J.E. Mottershead, A.Ihle, T. Siebert, H.R. Schubach, Finite element model updating from full-field vibration measurement using digital image correlation, *Journal of Sound and Vibration* 330 (8) (2011) 1599–1620.

[11] W. Wang, J. E. Mottershead, T. Siebert, A. Pipino, Frequency response functions of shape features from full-field vibration measurements using digital image correlation,

Mechanical Systems and Signal Processing 28 (2012) 333-347, http://dx.doi.org/10.1016/j.ymssp.2011.11.023.

[12] F. Trebuňa, R. Huňady, Z. Bobovský, M. Hagara, Results and experiences from the application of digital image correlation in operational modal analysis, *Acta Polytechnica Hungarica* 10 (5) (2013) 159-174, http://dx.doi.org/10.12700/APH.10.05.2013.5.10.

[13] H. Schreier, J.-J. Orteu, M.A. Sutton, *Image Correlation for Shape, Motion and Deformation Measurements: Basic Concepts,Theory and Applications*, Springer Science & Business Media, 2009.

[14] R. Huňady, M. Hagara, A new procedure of modal parameter estimation for high-speed digital image correlation, *Mechanical Systems and Signal Processing*, Volume 93, 1 September 2017, Pages 66-79.