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# Experimental identification of modal parameters of thin metal sheets by using of DIC

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## Abstract

This contribution deals with the application of modern optical noncontact method - digital image correlation (DIC) - by experimental modal analysis of thin metal sheets. The determination of mode shapes and modal frequencies was performed on sheet samples with simple squared and annular shapes. An optical device served for vibration investigation, created by components of Brüel & Kjær and Polytec companies, was used for independent validation of the results obtained by an additional program Modan, which has been developed at the Technical University of Košice. Two different types of vibration exciters were used to energize the samples - an acoustic white noise and a mechanical modal hammer.

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*Keywords*: digital image correlation, experimental modal analysis, thin sheet, Q-450 Dantec Dynamics, Modan

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**Nomenclature**

| | |
|---|---|
| $v$ | velocity (m/s) |
| $f$ | frequency (Hz) |
| px | pixel |
| fps | frames per second |
| CCD | charge-coupled device |
| $f_x$ | focal length of camera x |
| $O_x$ | origin of camera x coordinate system |

## 1. Introduction

An investigation of vibration is a very important part of engineering work. The understanding of modal frequencies and modal shapes allows prevent the technical machines from their untimely damage, performance reduction and negative increase of noise as well. These undesirable phenomena usually appear if the frequency of loading force corresponds with the modal frequency of system or its individual parts. This described phenomenon is known as resonance and typically has fatal outcomes.

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In general the modal frequencies can be acquired by three underlying techniques. For some systems with less of degrees of freedom it is possible to create so called physical model containing matrixes of mass, stiffness and damping, which can be solved analytically. The second possibility is the utilization of numerical methods. But in this case programs utilizing finite element method consider with ideal conditions (homogeneous material, ideal connections and fixtures, etc.), that does not have to completely correspond to reality. The last alternative is the performance of experimental modal analysis. The experiment can be directly done in-situ or after the system stop and disassembling of its investigated parts. In this case a modern optical experimental method – digital image correlation – was used to determine modal frequencies and mode shapes of thin sheet samples.

## 2. Digital image correlation

Digital image correlation is a modern optical method based on correlation principle of investigated object, which is shot by CCD cameras during its loading. The correlation process of acquired digital images, also called correlation, is performed gradually on small image elements called facets. Shape of this elements use to be squared with usual size from 15x15 to 30x30 pixels. Stochastic black and white pattern is created on the object surface in order to correlation of identical parts of the images. There are various methods for creation of finer or coarser patterns, but the easiest way is a creation of pattern by white and black spray paint.

Minimal size of facet is determined by size of created pattern. The every one facet has to contain white and black color in order to proper facets correlation.

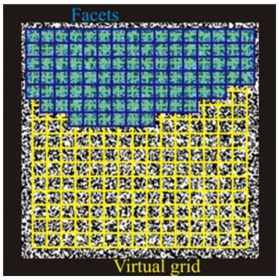


Fig. 1. Virtual grid and facets.

By digital image correlation method it is possible to determine displacement and strain fields. Values of displacements are determined in virtual grid corners created automatically by the software (Fig.1). Similarly, like by FEM programs where computation accuracy depends on size of finite element also the quality of results of digital image correlation depends on the size of virtual grid element. If the initial contour and displacement vectors of all element points are known, it is possible to compute its strains. Acquisition of strains is ensured either by differentiation of adjoining point displacements or by analysis of local facets curving used by correlation [1-4].

Two CCD cameras are generally used by performing of experimental tests with using of high-speed correlation system Q-450 Dantec Dynamics. It is possible to investigate objects spatial deformations of size from several mm$^2$ to some m$^2$ by using of these cameras. Such camera setting is conditioned by visibility of each investigated object point by both cameras simultaneously, what considerably complicate the investigation of objects with other than flat shape or objects with bigger surface rounding.

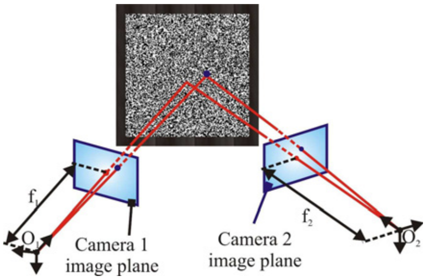


Fig. 2. Layout of stereoscopic configuration of cameras.

In general, CCD camera can not distinguish the size and distance of sampled objects and therefore mini-sized object observed from small camera distance can appear as big as macroscopic one situated further. For this reason the acquisition of correct information about object deformation is dependent on process precision, also called calibration of cameras. Particular camera calibration process of optical system Q-450 Dantec Dynamics uses Zhang's algorithm [5-6].

## 3. Experimental modal analysis of thin metal sheets

Till now the utilization of DIC with an additional program Modan by modal analysis was tested on different sheet samples with higher stiffness [7-15]. For this reason we accepted the investigation of metal sheets of the thickness 0.3mm as a challenge to perform measurements on samples which stiffness is noticeably smaller. It can cause some complication by performance of modal analysis such as sample banding or creation of such a fixture which does not ensure uniform conditions of sample along the whole surface.

The first experiment resided in modal analysis of sheet plate depicted in the Fig. 3a, fixed along its whole fringe. Using of spray paint the black and white random pattern was made on the plate surface. Two wooden frames were attached to the plate from both sides by eight woodscrews (Fig. 3a white color) a subsequently mounted with a subwoofer together by four screws (Fig. 3b red color). The subwoofer broadcasted an acoustic white noise and thus worked as a source of loading force (Fig. 3b).

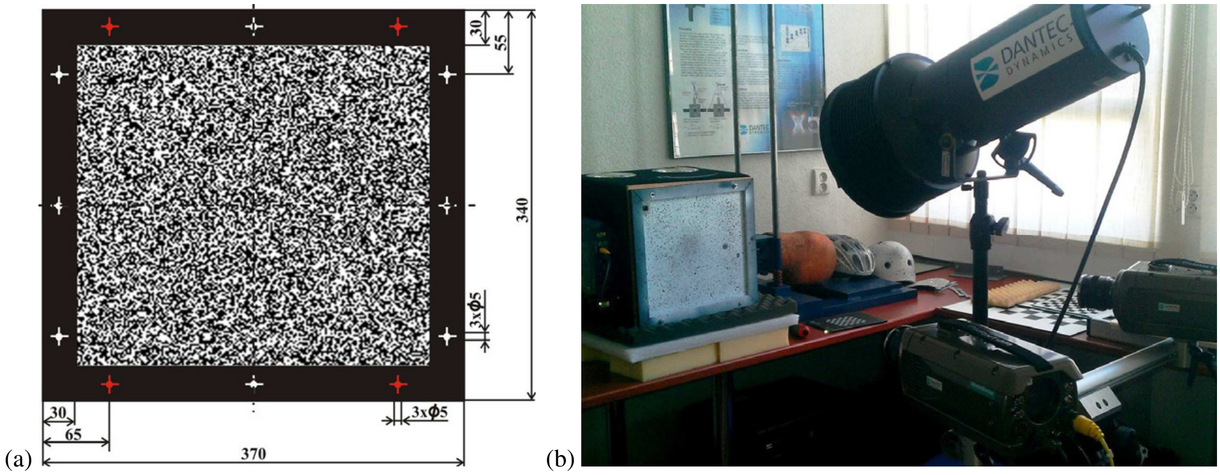


Fig. 3. Dimensions of investigated sample with wooden frame (a) and Q-450 cameras configuration (b).

As for the technical praxis only several initial modal frequencies and mode shapes are interesting, the frequency range of measurement was selected from 0Hz to 500Hz. For a reason of using FFT the sampling frequency of cameras was set to 1000fps. The cameras shutter times adjusted to maximal value 499µs set optimal light conditions by using of one high-performance point source of light. The apertures of objectives adjusted to focal ratio 22 set the maximum sharpness of obtained image.

Program Modan uses the most standard variant of fast Fourier transformation, which assumes that the number of data is an integer power of number 2. For the reason that by using of acoustic white noise a long time recording is not necessary, the acquisition time was set to 1,024s and system Q-450 captured 1024 pictures by both cameras.

Subsequently the cameras calibration was performed. It is carried out by rotation and moving of calibration target in the visual field of both cameras. The plastic calibration target Pl-23-WMB_9x9 with the square size of 23mm was employed. System Q-450 captured 15 pictures of this target in different location and automatically calculated the calibration parameters.

In ISTRA 4D (the control software of Q-450) a spectral analysis of measured and evaluated displacements was performed in order to obtain the frequency spectrum of displacements. The frequency spectrum of Z-displacements can be seen in the Fig. 4.

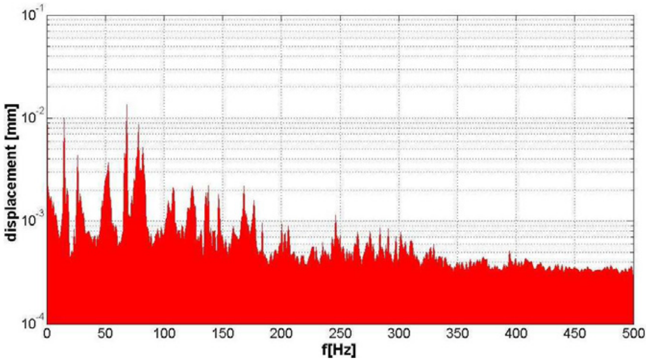


Fig. 4. Frequency dependence of sheet plate Z-displacements obtained by DIC.

However ISTRA 4D can not automatically assign mode shapes with correspondent frequencies and draw their. Therefore it was necessary to excite the sheet plate again and capture it by system Q-450. Harmonic sinusoidal signals with subsistent frequencies were used as exciter. Three chosen mode shapes obtained by ISTRA 4D can be seen in the Fig. 5.

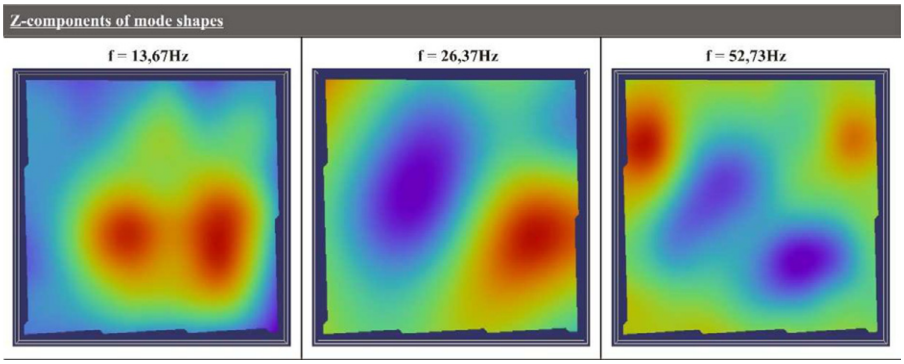


Fig. 5. Chosen Z-components of mode shapes obtained by ISTRA 4D.

Of course such obtaining of mode shapes is relatively time consuming. For that reason the program Modan was developed to get modal frequencies and mode shapes of investigated objects faster and more simply. The exported data from ISTRA 4D in HDF5 format were imported into Modan and then processed. Correspondent mode shapes of plate vibration obtained by Modan are visible in the Fig. 6. The use of Modan has some advantages over the process described above – in particular shorter duration of the whole process and automatic searching and depicting of shape with maximal amplitude of vibration as well.

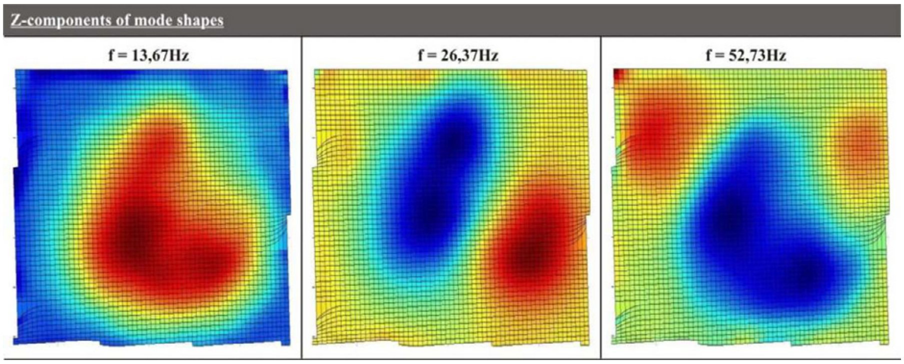
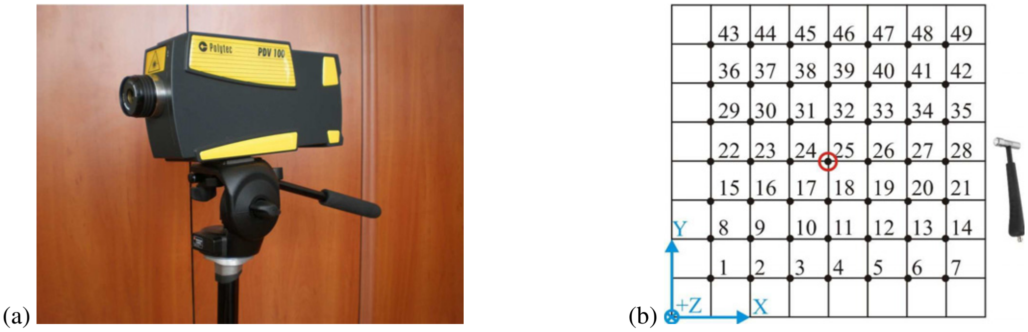


Fig. 6. Chosen Z-components of mode shapes obtained by Modan.

By using of Pulse6 apparatus from Brüel & Kjær an independent experiment was performed for validation of the reached results. The aim of the experiment was excite the whole plate surface by modal hammer Brüel & Kjær 8206 and the response of the plate scan with a laser scanner of vibration velocity PDV-100 from Polytec (Fig. 7a). This sensor uses Doppler principle, is light and portable. It can be used for measurements outside of the laboratories and manages to record vibration in frequency range from 0Hz to 22kHz up to distance of 30m.

The form of virtual grid simulated the plate surface, created in software MTC Hammer can be seen in the Fig. 7b. Each grid point marked by a number from 1 to 49 was excited gradually by modal hammer. The system response was measured by PDV-100 in the point 25 (marked by red circle). The hammer impact was realized three times at each point in the perpendicular direction to the sheet surface and responses together with excitation forces were recorded and averaged in order to get more accurately results.



(a) (b)

Fig. 7. Laser scanner of vibration velocity PDV-100 (a) and virtual grid simulated the sheet plate surface with modal hammer Brüel & Kjær 8206 (b).

The frequency dependence of velocity in the positive Z direction of one of grid points obtained by MTC Hammer can be seen in the Fig. 8.

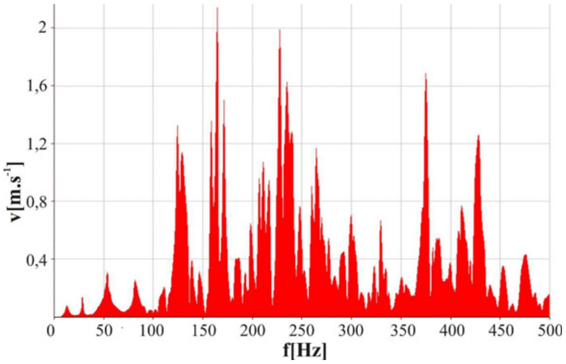


Fig. 8. Frequency dependence of velocity in the positive Z-direction of the grid point 27.

Due to a high number of acquired modal frequencies we list just first fifteen frequencies obtained by both independent experimental methods (Table 1.) We can say that they are coincidence. Also first two mode shapes depicted in the Fig. 9 correspond. We think that the cause of deviation in the third mode shape consists in applied sources of excitation and especially in the sensitivity of particular systems. While by using of Pulse6, specialized for vibration analysis, the modal frequencies were captured in the entire frequency range, by using of DIC just approximately to 330Hz.

Table 1. Modal frequencies obtained by Modan and MTC Hammer.

| | $f_1$ [Hz] | $f_2$ [Hz] | $f_3$ [Hz] | $f_4$ [Hz] | $f_5$ [Hz] | $f_6$ [Hz] | $f_7$ [Hz] | $f_8$ [Hz] | $f_9$ [Hz] | $f_{10}$ [Hz] | $f_{11}$ [Hz] | $f_{12}$ [Hz] | $f_{13}$ [Hz] | $f_{14}$ [Hz] | $f_{15}$ [Hz] |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Modan** | 13,7 | 26,4 | 52,7 | 68,4 | 78,1 | 107,4 | 124 | 137,7 | 146,5 | 159,2 | 168 | 172,8 | 183,6 | 200,2 | 206,1 |
| **MTC** | 14,1 | 26,9 | 53,1 | — | 78,4 | 108 | 124,4 | 138,2 | 147 | 159,6 | 167,7 | 173,3 | 184,1 | 199,7 | 205,8 |

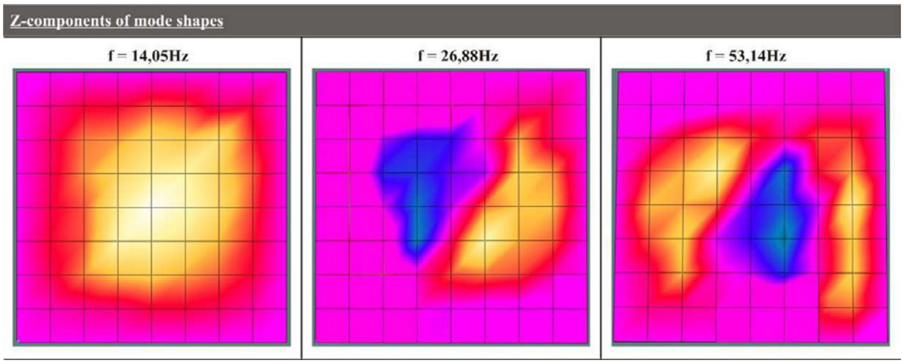


Fig. 9. Chosen Z-components of mode shapes obtained by MTC Hammer.

The results of modal analysis done just by finite element methods are visible in the Fig. 10. The difference in mode shapes can be caused by creating of non-ideal fixture between sheet and wooden frames or by imperfect attachment of frames with subwoofer. Likewise non-homogeneous properties of thin sheet (inconsiderable change of its thickness or its imperfect tightening in the wooden frame) can cause basic difference of mode shapes.

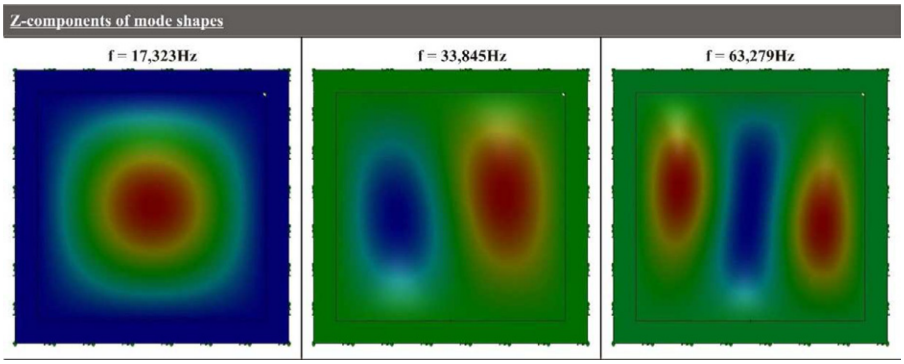


Fig. 10. Chosen Z-components of mode shapes obtained by SolidWorks2010.

The second experiment consisted in carrying-out modal analysis of the same sheet of an annulus shape (Fig. 11a). The sample was again excited by acoustic white noise and moreover loaded by uniaxial tension of three levels 0N, 40N and 80N.

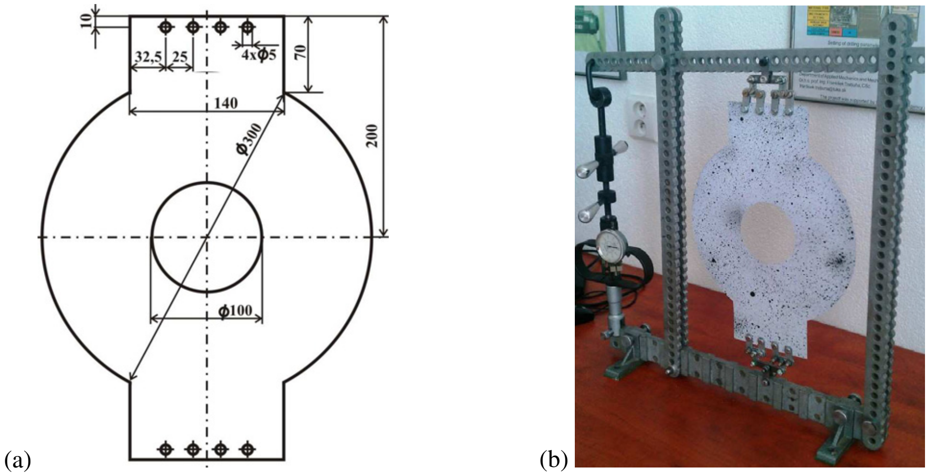


Fig. 11. Dimensions of the investigated sample of an annulus shape (a) and loading construction with fixed sample (b).

All cameras parameters and acquisition time were adjusted likewise the first experiment described above. After data export of all three measurements into Modan subsequent frequency spectra were obtained.

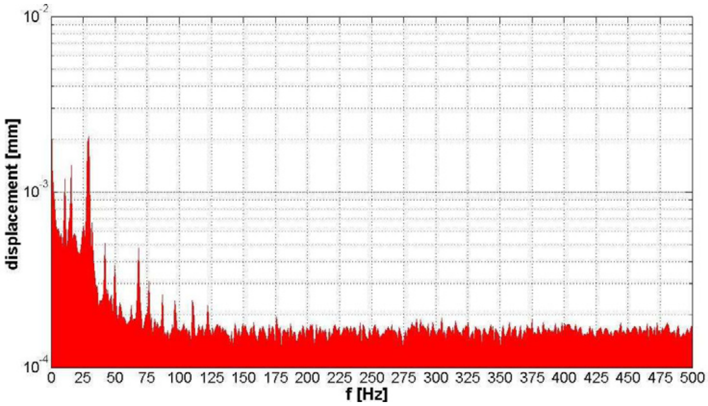


Fig. 12. Frequency dependence of variantion in Z direction obtained by uniaxial loading 0N by Modan.

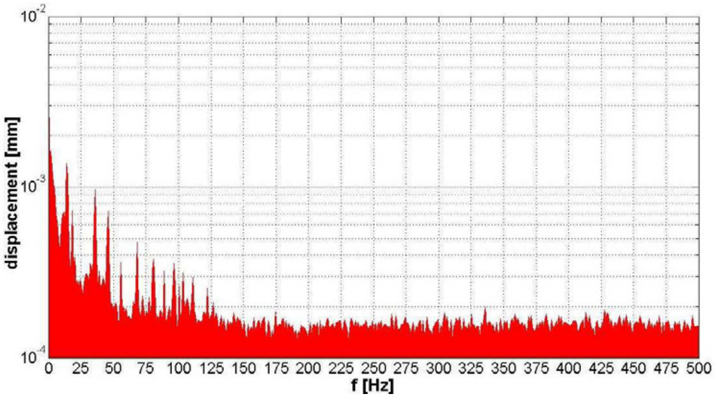


Fig. 13. Frequency dependence of variantion in Z direction obtained by uniaxial loading 40N by Modan.

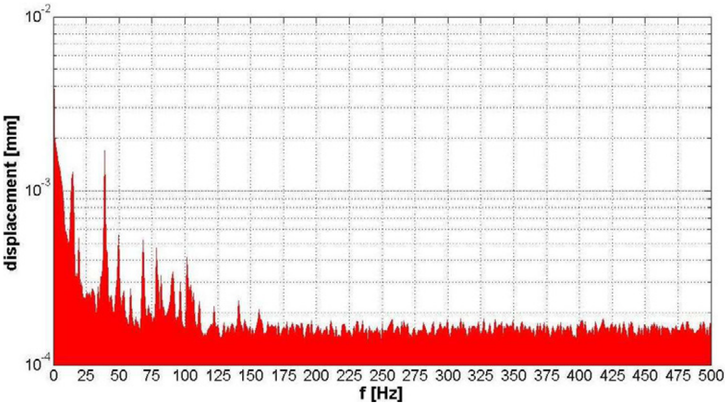


Fig. 14. Frequency dependence of variantion in Z direction obtained by uniaxial loading 80N by Modan.

Table 2 lists the modal frequencies deducted from the previous charts. The sensitivity of Q-450 and noise emergent by thin sheets vibration made the identification of modal frequencies in frequency range from 160Hz to 500Hz impossible. For that reason we introduce only distinguishable modal frequencies in frequency range 0-160Hz.

Table 2. Modal frequencies obtained by three different uniaxial loading by Modan

| | $f_1$ [Hz] | $f_2$ [Hz] | $f_3$ [Hz] | $f_4$ [Hz] | $f_5$ [Hz] | $f_6$ [Hz] | $f_7$ [Hz] | $f_8$ [Hz] | $f_9$ [Hz] | $f_{10}$ [Hz] | $f_{11}$ [Hz] | $f_{12}$ [Hz] | $f_{13}$ [Hz] | $f_{14}$ [Hz] | $f_{15}$ [Hz] |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **0N** | 10,7 | 15,6 | 31,3 | 42 | 49,8 | 68,4 | 76,2 | 86,9 | 95,8 | — | 103,5 | 110,4 | 121 | — | — |
| **40N** | 13,7 | 17,6 | 36,1 | 45,9 | 55,7 | 68,4 | 80 | 88,9 | 96,7 | 100,6 | 103,5 | 111,3 | 122 | — | — |
| **80N** | 15,6 | 19,5 | 40 | 49,8 | 58,6 | 68,4 | 82 | 90,8 | 96,7 | 101,6 | 104,5 | 111,3 | 122 | 140,6 | 156,3 |

It is evident, that by increasing loading when also the sample stiffness is increasing, the values of modal frequencies are higher. The remarkableness of obtained results lies in fact, that from certain frequency the differences between modal frequencies are not so significant and actually the frequencies are the same. Several mode shapes obtained by Modan can be seen in the Fig. 15.

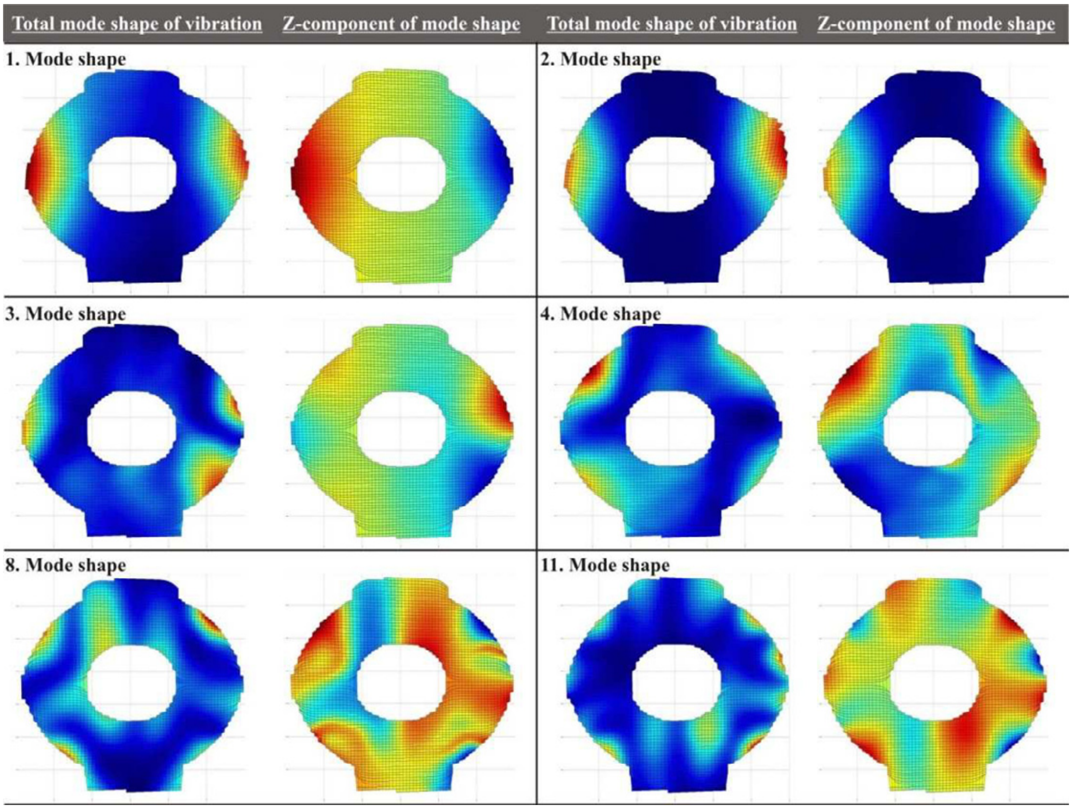


Fig. 15. Chosen mode shapes obtained by Modan.

***Annotation:*** The frequency of 68,4Hz obtained in all measurements by DIC is the frequency of cameras fan (mentioned by manufacturer).

## 4. Conclusion

Two experimental procedures of modal parameters obtaining of thin sheets are described in this contribution. After the results validation by independent experimental and numerical methods we conclude, that the using of digital image correlation is convenient for vibration analysis, but with some limitations. By investigation of less stiff objects it can be an unacceptable noise, which can express itself so much, that in certain frequency range it is not possible to simply determine modal frequencies. Vice versa by investigation of stiffer objects it can happen, that Q-450 does not record such amount of modal frequencies as specialized systems developing for vibration analysis. We assume shorter duration of modal parameters obtaining to be the advantage of using DIC by modal analysis. The second benefit of using DIC is its application by modal investigation of objects with more complicated contour and fixture.

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## References

[1] Siebert, T., Splitthof, K., Stecklum, S., Herbst, C., 2005. "New features in digital image correlation techniques", 22nd DANUBIA-ADRIA Symposium on Experimental Methods in Solid Mechanics, Parma.

[2] Trebuňa, F., Šimčák, F., 2007. Príručka experimentálnej mechaniky, TypoPress, Košice, Slovensko.

[3] Huňady, R., 2010. Možnosti využitia metódy digitálnej obrazovej korelácie v aplikáciách dynamiky. Dizertačná práca. Technická univerzita v Košiciach, Strojnícka fakulta, Košice.

[4] Hagara, M., 2012. Uplatnenie metód obrazovej korelácie v dynamike mechanických sústav. Písomná práca k dizertačnej skúške. Technická univerzita v Košiciach, Strojnícka fakulta, Košice.

[5] Zhang, Z., 1998. "A Flexible New Technique for Camera Calibration", Microsoft Research Technical Report MSR-TR-98-71, Microsoft Corporation, Redmond, WA 98052, 2 December 1998.

[6] Zhang, Z., 2000. "A Flexible New Technique for Camera Calibration", IEEE TRANACTIONS ON PATTERN ANALYSIS AND MACHINE INTELLIGENCE [online], November 2000, vol. 22. no. 11, p. 1330-1334. URL: <http://research.microsoft.com/en-us/um/people/zhang/papers/zhangpami-02-calib.pdf>

[7] Huňady, R., 2009. "Návrh algoritmu pre spracovanie a vizualizáciu výsledkov modálnej analýzy", Novus Scientia 2009 : 11. celoštátna konferencia doktorandov Strojníckych fakúlt technických univerzít a vysokých škôl, . Technická univerzita v Košiciach, Strojnícka fakulta, Košice, p. 394-399.

[8] Trebuňa, F., Huňady, R., 2010. Využitie digitálnej obrazovej korelácie na určovanie vlastných tvarov a frekvencií sústavy. In *"Jemná mechanika a optika"*, Vol. 55, no. 10 (2010), p. 276-279.

[9] Trebuňa, F., Huňady, R., Znamenáková, M., 2010. "Using of digital image correlation method for expeirmental determination of modal parameters", Experimental Stress Analysis – Proceedings of the 48th International Scientific Conference, Velké Losiny, Czech republic, p. 451-458.

[10] Huňady, R., Bobovský, Z., Hagara, M., 2011. "Methodology for determination of modal parameters by digital image correlation", Moddeling of Mechanical and Mechatronical Systems – Proceedings of the 4th International Conference, Herľany, Slovakia, p. 193-201.

[11] Trebuňa, F., Huňady, R., Bobovský, Z., Hagara, M., 2011. An application of high-speed digital image correlation in determination of modal parameters. In *"Acta Mechanica Slovaca"*, vol. 15, no. 4 (2011).

[12] Hagara, M., Huňady, R., Štamborská, M., 2011. "An application of binocular digital image correlation in determination of modal parameters of flat objects with more complicated contour", Moddeling of Mechanical and Mechatronical Systems – Proceedings of the 4th International Conference, Herľany, Slovakia, p. 142-150.

[13] Hagara, M., Huňady, R., Štamborská, M., 2011. "Using of digital image correlation in experimental modal analysis of a horizontal stabilizer of the airplane model Phoenix Trainer60", Moddeling of Mechanical and Mechatronical Systems – Proceedings of the 4th International Conference, Herľany, Slovakia, p. 151-159.

[14] Hagara, M., Kalina, M., Schrötter, M., 2012. Vyšetrovanie kmitania dverí automobilu využitím metódy digitálnej obrazovej korelácie. In *"ATP Journal Plus"*, no. 1 (2012), p. 66-70.

[15] Hagara, M., Schrötter, M., 2012. "Metodika pre vykonávanie experimentálnej modálnej analýzy častí lietadiel pomocou metódy digitálnej obrazovej korelácie s využitím doplnkového programu Modan 1.0", Zborník príspevkov z konferencie – II. Vedecká konferencia doktorandov LF, Košice, Slovensko.