The use of Modan 3D in experimental modal analysis

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Keywords: digital image correlation, Modan 3D, experimental modal analysis, PULSE

Abstract. Experimental modal analysis is a relatively young part of dynamics, which deals with the vibration modes identification of machines or their parts. Its development has started since the beginning of the eighties, when the computers' hardware equipment has improved and the fast Fourier transform (FFT) could be used for the results determination. Nowadays it provides an uncountable set of vibration analysis possibilities starting with conventional contact transducers of acceleration and ending with modern noncontact optical methods. In this contribution we mention the use of high-speed digital image correlation by experimental determination of mode shapes and modal frequencies. The aim of our work is to create a program application called Modan 3D enabling the performing of experimental modal analysis and operational modal analysis. In this paper the experimental modal analysis of a thin steel sample performed with Q-450 Dantec Dynamics is described. In Modan 3D the experiment data were processed and the vibration modes were determined. The reached results were verified by PULSE modulus specialized for mechanical vibration analysis.

Introduction

A case called resonance is a very dangerous phenomenon leading mainly to the fatal consequences. For this reason a determination of natural frequencies and mode shapes of constructions is the basic work for constructor. To avoid this undesirable phenomenon it is necessary to identify it and to use systems in safe frequency domain [1]. The methods for modal parameters identification can be divided into two main groups:

- theoretical,
- experimental.

The theoretical methods are represented by various programs based on a finite element model principle [2]. In experimental modal analysis the modal frequencies, the mode shapes and damping ratios respectively are estimated from experimentally obtained data set. The principle of this technique is based on a relation between excitation and responses in different locations of the investigated sample in frequency domain [3].

Background of experimental modal analysis

The dynamic behavior of any mechanical system can be described in frequency domain by Frequency Response Functions (FRFs). Consider the model of MDOF system with N degrees of freedom. Its FRFs can be written as a function of the complex poles as follows:

$$\mathbf{H}(j\omega) = \sum_{i=1}^{N} \left(\frac{\mathbf{R}_r}{j\omega - \lambda_r} + \frac{\mathbf{R}_r^*}{j\omega - \lambda_r^*} \right) \qquad (1)$$

The poles are expressed by $\lambda_r = \sigma_r + j\omega_r$, where σ_r is the damping factor, and ω_r is the damped natural resonance frequency.

If the poles are considered as eigenvalues of a system, its eigenvectors can be interpreted as the modal shapes, where each eigenvector corresponds with a specific eigenvalue. The residues $\mathbf{R}_r$ are described by equation:

$$\mathbf{R}_r = \mathbf{\Psi}_r \, \gamma_r^T \tag{2}$$

where γ_r is the modal participation vector, $\mathbf{\Psi}_r$ is the mode shape. All those parameters are specified for the r-th mode.

Frequency response function can also be expressed as the ratio between output (response) and input (excitation) as a function of frequency [3]:

$$\mathbf{H}(j\omega) = \frac{\mathbf{Y}(j\omega)}{\mathbf{X}(j\omega)} \tag{3}$$

This concept is commonly used in practical applications.

Modal parameter estimation is a special case of system identification where the model of the system can be expressed in the form of modal parameters. There exist several estimation algorithms that are being used in time or frequency domain. One of them is Normal Mode Indicator Function (NMIF) that is calculated as [4]:

$$\text{NMIF}(j\omega) = \frac{\sum\limits_{k=1}^{N}\left|\text{Re}\left(H_k(j\omega)\right)\right|^2}{\sum\limits_{k=1}^{N}\left|H_k(j\omega)\right|^2} \tag{4}$$

At a given resonant frequency, the real portion of the FRF corresponds to the response of all of the structural modes with natural frequencies away from the given natural frequency, while the magnitude term in the denominator corresponds to response of all modes. If a mode shape is adequately excited, its magnitude will be much greater than the response of modes away from the natural frequency, and therefore the NMIF will be minimized (Fig. 1). A value of the NMIF below a threshold at a resonant frequency implies that the corresponding mode has been sufficiently excited to identify that mode.
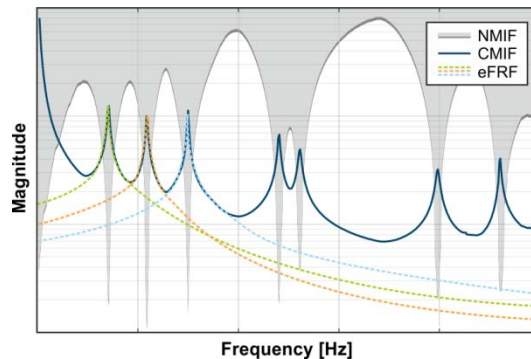

Fig. 1 Plot example of NMIF, CMIF and eFRF

The next estimation algorithm, title Complex Mode Indicator Function (CMIF), is based on singular value decomposition (SVD) of the FRF matrix at each spectral line:

$$\mathbf{H}(j\omega) = \mathbf{U}(j\omega)\,\mathbf{S}(j\omega)\,\mathbf{V}(j\omega)^H \tag{5}$$

where $\mathbf{U}(j\omega)$ is the left singular matrix, $\mathbf{V}(j\omega)$ is the right singular matrix and $\mathbf{S}(j\omega)$ is the matrix of singular values. CMIF is then expressed as [5]:

$$\mathbf{CMIF}(j\omega) = \text{diag}\big(\mathbf{S}(j\omega)\big) \qquad (6)$$

The CMIF plot is therefore defined as the plot of the diagonal elements of singular value matrix. Damped natural frequency is the frequency at which the maximum magnitude of the singular value occurs, thus the peaks in CMIF plot indicate the existence of modes (Fig. 1). CMIF can be applied to multiple or single reference FRF measurements and is capable to indicate the existence of real normal or complex modes and the relative magnitudes of each mode.

By using the enhanced Frequency Response Function (eFRF), it is possible to isolate individual modes (Fig. 1). eFRF is defined as a weighted average of all of the measured FRFs. The singular vectors $\mathbf{u}(j\omega_r)$ and $\mathbf{v}(j\omega_r)$ obtained from SVD are used as weighting functions. Thus for the r-th mode [5]:

$$\text{eFRF}(j\omega)_r = \mathbf{u}(j\omega_r)^H \mathbf{H}(j\omega)\, \mathbf{v}(j\omega_r). \qquad (7)$$

The Modal Assurance Criterion (MAC) can be used to investigate the validity of estimated modes. MAC is a mathematical tool to compare two vectors to each other. The MAC value between two mode shape vectors $\{\Psi\}_r$ and $\{\Psi\}_s$ is calculated as [4, 6]:

$$\text{MAC}_{r,s} = \frac{\left|\Psi_r^H \Psi_s\right|^2}{\Psi_r^H \Psi_r\ \Psi_s^H \Psi_s} \qquad (8)$$

The MAC takes the values from the interval $0 \div 1$. If the MAC is equal to 1, mode shape vectors $\{\Psi\}_r$ and $\{\Psi\}_s$ are the same mode shape. If they are different the MAC value should be low, due to the orthogonality condition of the mode shapes.

The use of Modan 3D in experimental modal analysis

Modan 3D is a modal analysis software tool intended for the high-speed digital image correlation system Q-450 Dantec Dynamics [7, 8]. It is being developed at the Department of Applied Mechanics and Mechatronics, Faculty of Mechanical Engineering, Technical University of Košice, Slovakia.

The block diagram depicted in the Fig. 2 shows the basic principle of Modan 3D part for experimental modal analysis.
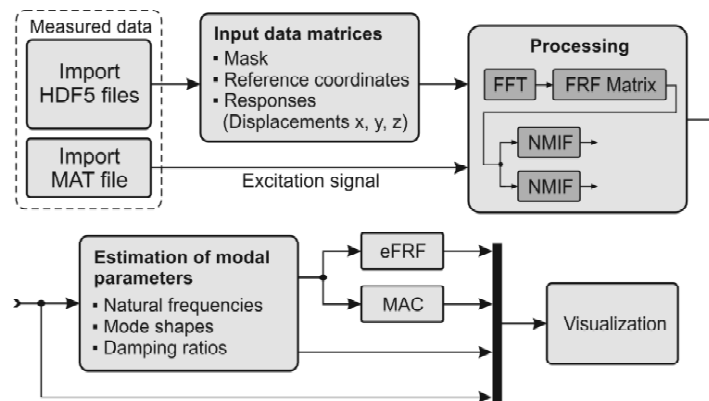

Fig. 2 Principle scheme of Modan 3D software as a tool for experimental modal analysis

In the case of experimental modal analysis is needed to measure an excitation signal from an impact hammer or a shaker. For this purpose, a special script has been created in Matlab. Its main

task is to record an input signal and to activate trigger of the system Q-450. The block scheme in Fig. 3 illustrates the principle connection of individual devices during the measurement process. It was necessary to use some additional devices: CCLD amplifier serving to amplify a signal from an impact hammer, and AD/DA converter that digitalizes input and sync signal and generates a signal for the trigger.
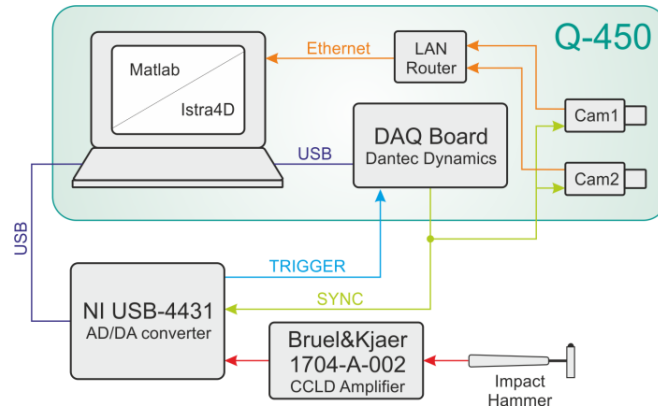

Fig. 3 Scheme of the connection of the system Q-450 and additional devices during the experimental modal analysis

Experimental modal analysis performed by Q-450 with the using of Modan3D

As the realization of this experiment was performed in light of the results credibility verification an investigated sample was a thin steel plate. Its thickness was 0.8mm, dimensions 150x150mm and it was fixed to the pedestal in its center of gravity.

The modal hammer Brüel&Kjær 8206 with plastic head was used to excite the sample. The sample frequency of cameras was set to 2000 fps.
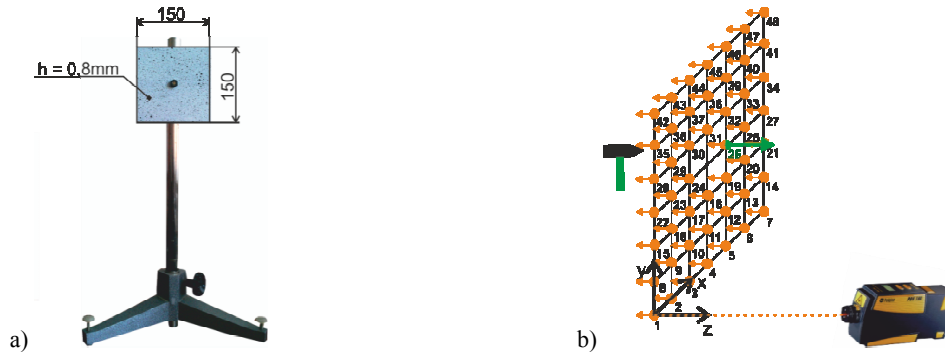

Fig. 4 a) Dimensions and fixture of the sample, b) Principal scheme of measured and excited points by using of PULSE

The results obtained by Modan 3D were for the need of plausibility validation checked by the modulus PULSE specialized for mechanical vibration analysis. In the program MTC Hammer, in which the modal analysis was done, a virtual grid created by 6x6 squares was made. On the edges of these squares the sample displacement velocity in Z direction was measured by laser vibrometer PDV100. The excitation was performed by the same modal hammer.

A graphical visualization of the results obtained by both independent experiments can be seen in the Fig. 5, Fig. 6.
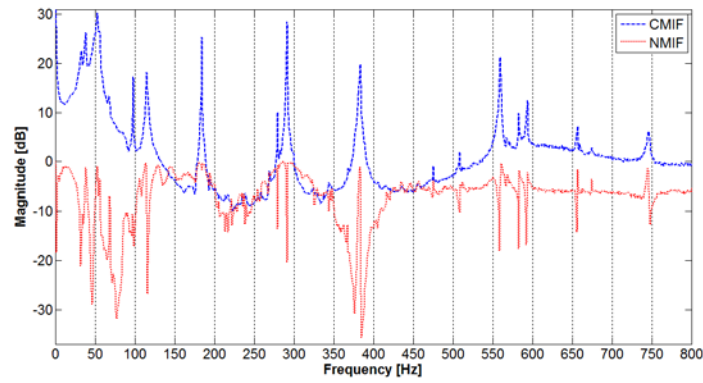
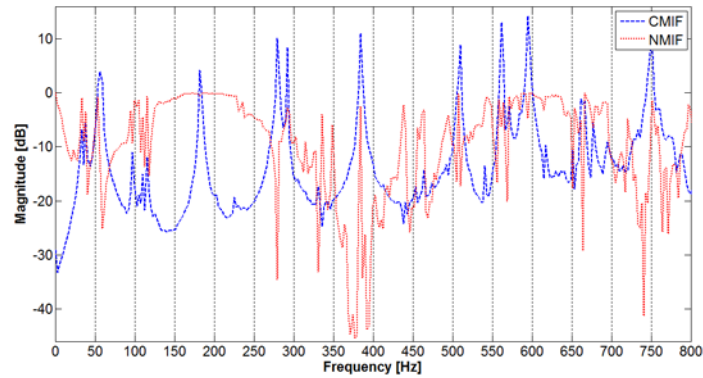Fig. 5 CMIF and NMIF functions obtained by Modan 3D

Fig. 6 CMIF and NMIF functions obtained by PULSE

In the Fig. 8 the mode shapes obtained by Modan 3D and PULSE are depicted. By the use of Modan 3D also the damping ratios were computed. For this purpose the 3dB rule was used.
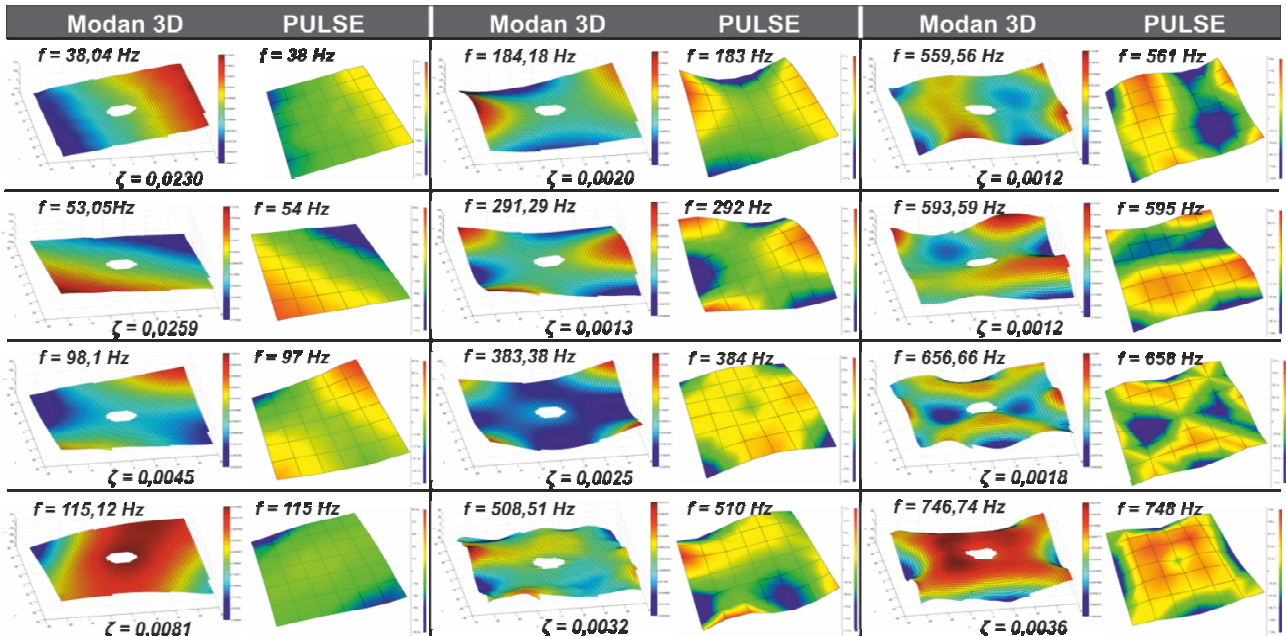

Fig. 8 A comparison of mode shapes obtained by Modan 3D and PULSE

Summary

The use of two independent methods proves that the results acquired by using of digital image correlation together with program Modan3D have acceptable quality level responding to used method.

Modan3D as a tool for experimental modal analysis even now markedly simplifies and makes faster the process of natural frequencies and mode shapes identification. By using of hardware configuration mentioned above Modan3D with all its parts can become a complex tool for vibration analysis.

Acknowledgement

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