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COMPARISON OF THE EXPERIMENTALLY OBTAINED DYNAMIC CHARACTERISTICS OF A BRIDGE WITH AMBIENTAL AND FORCED VIBRATIONS

BY

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Abstract. The paper presents a study case performed on a bridge over the Danube, located in Cernavoda, Romania. The tested structure was subjected to several vibrations, resulted from the natural movement of the bridge and from the movement of a truck, a train and an excavator. The monitoring system used to record the in situ data was composed of four seismic transducers positioned in the first span of the bridge. The speed integration and vibration modes identification was performed using ARTeMIS Extractor. Emphasis is placed on analysing the mode shapes and observing the relation between frequency and modal coordinates.

Key words: dynamic characteristics; frequency; vibration modes; FDD; MAC.

1. Introduction

The *in situ* determined dynamic characteristics of a structure are an indicator on the degradation state of the building. Because the excitation of the rigid structures is hard to accomplish, the frequencies and the vibration modes are identified using ambiental (*e.g.* wind) and forced (*e.g.* traffic on the bridge:

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movement of a truck, a train and an excavator) excitation sources (Bien & Zwolsky, 2007; Farrar *et al.*, 1999). Usually, the level of the ambiental vibrations only is low and imposes the use of transducers with high sensitivity acceleration or speed.

For a structure in the elastic domain the measured dynamic characteristics are influenced by the non-structural elements so the dynamic measurements at reduced vibrations present a disadvantage.

To analyse the difference between the experimentally determined dynamic characteristics at various vibration levels, dynamic measurements in a span of a bridge were performed. The dynamic identification was performed using the Frequency Domain Decomposition (FDD) method, a modern method based only on the measurement of the structure response.

2. Experimental Program

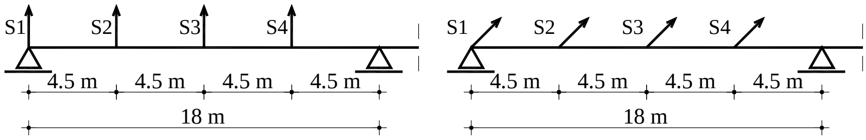
The analysed structure is the Danube Channel – Black Sea bridge on the European Road E81, located in Cernavoda, a city in Romania. The bridge has spans of 18 meters and the load bearing structure is composed of reinforced concrete columns and transversal girders and steel longitudinal girders (Fig. 1).

a *b*

Fig. 1 – General view of the bridge: *a* – lateral view; *b* – view on top of the bridge.

The dynamic measurements have been made using 4 SS1 Kinematrics seismic transducers, which were positioned on the marginal opening of the bridge. They were placed according to Fig. 2 as follows:

a) in the marginal support, transducer denoted with S1;
b) at a quarter from the support, transducer S2;
c) in the middle of the span, transducer S3;
d) at three quarters from the support, transducer S4.



a *b*

Fig. 2 – Outline of the transducers positioning:
a – on the vertical direction; *b* – on the horizontal direction.

The seismic transducers have been oriented on vertical, Fig. 3 *a*, and transverse horizontal direction, Fig. 3 *b*, on the bridge.

a *b*

Fig. 3 – Transducers orientation:
a – on vertical direction; *b* – on horizontal direction.

On the bridge there have been several naturally obtained vibrations used as an excitation source from:

i) a train passing near the bridge;

ii) an excavator hitting the ground with the bucket;

iii) a 16 tonne truck passing with and without an obstacle on the runway, Fig. 4, at different speeds with and without braking.

a *b*

Fig. 4 – *a* – A truck as an excitation source;
b – runway with an obstacle.

The difference between the nature of these vibrations and their amplitude is easily noticed.

In the following is analysed if the dynamic characteristics (the periods of vibration, the critic damping fraction and the eigenshapes) are different with respect to the excitation source.

2.1. Dynamic Identification Using the Frequency Domain Decomposition Method

The Frequency Domain Decomposition (FDD) (Brinker *et al*, 2000) method is based on expressing the structure response with respect to the vibration modes. The method is an extension of the classic method, Basic Frequency Domain (BFD), based on the frequency domain (Stefan, 2001) often called as the peak-picking technique (Batel, 2002).

The spectral matrix is decomposed in a set of functions of auto spectral density which correspond to a model with one dynamic degree of freedom. The results have high precision if the excitation is white noise, the structure is lightly damped and the vibration modes are orthogonal from geometric point of view.

The relation between the unknown input $x(t)$ and the measured output $y(t)$ can be expressed with the following relation:

$$\left[G_{yy}(j\omega)\right]=\overline{\left[H(j\omega)\right]}\cdot\left[G_{xx}(j\omega)\right]\cdot\left[H(j\omega)\right]^{T}, \tag{1}$$

where: $[G_{xx}(j\omega)]$ is the input power spectral density matrix (PSD) with $r \times r$ dimensions, r is the inputs number; $[G_{yy}(j\omega)]$ – output power spectral density matrix with $m \times m$ dimensions, m is the outputs number; $[H(j\omega)]$ – frequency response function (FRF) of the system with $m \times r$ dimensions, “-“ – complex conjugate of the matrix; T – matrix transpose.

Asumming the input is given only by the white noise, the input matrix is constant.

$$[G_{xx}\left(j\omega\right)]=[C]. \tag{2}$$

In the Frequency Domain Decomposition method (FDD) the output power spectral density matrix $G_{yy}(j\omega)$ estimation (Singular Value Decomposition technique (SVD)) is made for each frequency f_k adequate to a peak k from the Fast Fourier Transform (FFT) analysis

$$\left[G_{yy}(j\omega)\right]_k=\begin{bmatrix}\mathrm{PSD}_{11}(j\omega) & \mathrm{CSD}_{1n}(j\omega)\\ \mathrm{CSD}_{n1}(j\omega) & \mathrm{PSD}_{nn}(j\omega)\end{bmatrix}_k \tag{3}$$

where: PSD($j\omega$) – power spectral density; CSD($j\omega$) – cross spectral density; n – number of the measurement points

$$[G_{yy}(j\omega)]=\left[V\right]\left[S\right]\left[V\right]^{H}=s_1v_1v_1{}^{H}+s_2v_2v_2{}^{H}+....+s_nv_nv_n{}^{H} \tag{4}$$

where: [V] is the vectors matrix; [S] – values matrix.

For each peak k a set of eigenvalues and eigenvectors according to the n^{th} number of the measurement channels can be determined. Because a part of the peaks do not correspond to the structure vibration modes (could be from an external excitation source) have to be verified for orthogonality using the Modal Assurance Criterion (MAC) (Allemang, 2003).

2.2. Modal Assurance Criterion

The Modal Assurance Criterion (MAC) is defined as a constant which gives the linearity degree between two reference modal vectors as follows:

$$MAC(\phi_i^A \phi_i^B) = \frac{\left| \{\phi_i^A\}^T \{\phi_i^B\} \right|^2}{\{\phi_i^A\}^T \{\phi_i^B\} \{\phi_i^A\}^T \{\phi_i^B\}}, \text{ (Li } et\ al\text{, 2011),} \tag{5}$$

where: ϕ_i^A, ϕ_i^B is the mode shape vectors.

The Modal Assurance Criterion takes values starting from zero, situation in which we have no correspondence between the two mode shape vectors, up to one, situation when we have perfect correspondence between the two.

3. The analysis of the Results

To be able to estimate the vibrations level, the displacements for each excitation source have been determined using the integration of the speeds recorded with the data acquisition system. Speeds integration and vibration modes identification were performed using the dynamic identification program ARTeMIS Extractor 2011.

The reduced values of the displacements resulted from natural excitation, when compared to the ones given by the passing of the truck over the bridge, can be observed in Table 1.

Table 1
Maximum Dynamic Displacements on the Vertical Direction

Action	Maximum vertical dynamic displacement (mm)			
	S1	S2	S3	S4
Truck passing with 40km/h	0.06411	0.12002	0.06301	0.07611
Truck passing with 30km/h	0.00523	0.09651	0.04813	0.05221
Truck passing with 10km/h, with braking	0.01298	0.04901	0.04605	0.05808
Excavator over an obstacle	0.00205	0.02766	0.04776	0.03278
Natural movement	0.00026	0.00092	0.00137	0.00097
Excavator with bucket	0.00008	0.00039	0.00060	0.00034

Table 2 summarizes the results in terms of displacements obtained from the transducers on the horizontal direction.

Table 2
Maximum Dynamic Displacements on Horizontal Direction

Action	Maximum horizontal dynamic displacement (mm)			
	S1	S2	S3	S4
Train and excavator bucket hits	0.00172	0.00158	0.00188	0.00244
Train	0.00054	0.00090	0.00201	0.00176

The ARTeMIS Extractor program has the option to identify, through the Frequency Domain Decomposition (FDD) technique, the shapes, frequency and critical damping fraction of the vibration modes using only the system output. The computation model is displayed in Fig. 5.

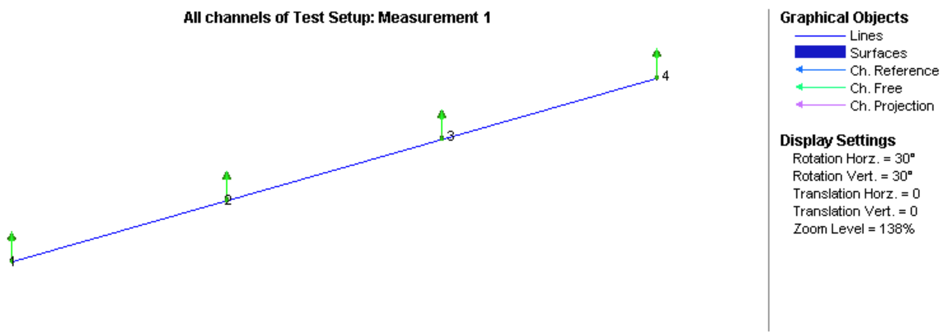


Fig. 5 – Computation model.

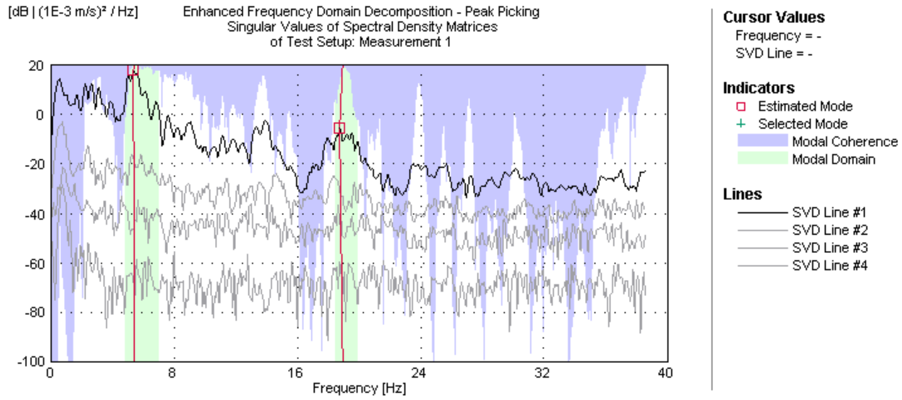


Fig. 6 – Dynamic identification using the FDD method.

When using the Frequency Domain Decomposition method (Fig. 6), the program has the option to automatically find the peaks and identifies only the orthogonal vibration modes. The orthogonality of the modes is checked using the Modal Assurance Criterion (MAC) (Fig. 7).

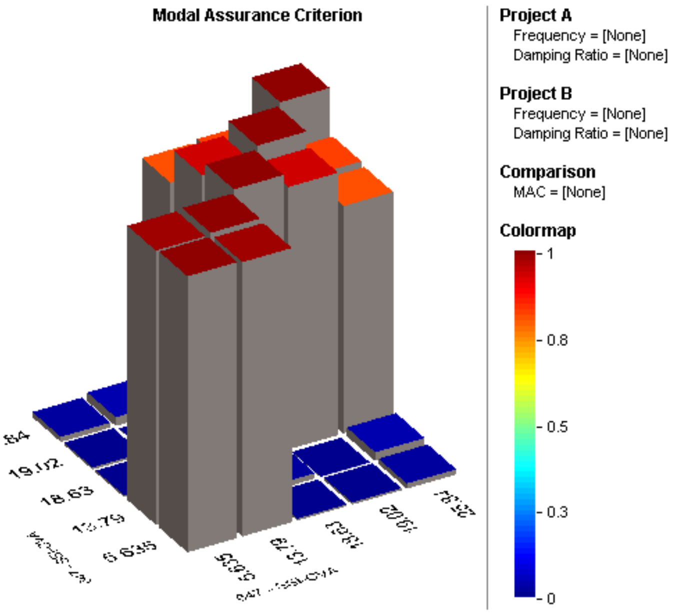


Fig. 7 – Modal Assurance Criterion.

By means of the FDD method more eigenmodes have been identified but after the orthogonality check, using the Modal Assurance Criterion, was found that only two of the five vibration modes are orthogonal.

The dynamic characteristics on the vertical direction, in terms of frequency, of the two valid modes are presented in Table 3.

Table 3

Dynamic Characteristics on the Vertical Direction

Action	Mode 1	Mode 2
	Frequency, [Hz]	Frequency, [Hz]
Truck passing with 40km/h	6.110	19.60
Truck passing with 30km/h	5.441	18.95
Truck passing with 10km/h, with braking	5.635	18.63
Excavator over an obstacle	6.193	19.32
Natural movement	6.282	19.61
Excavator with bucket	6.364	18.77

On the horizontal direction only one vibration mode was identified and the dynamic characteristics obtained are summarized in Table 4.

Table 4
Dynamic characteristics on the horizontal direction

Action	Mode 1
	Frequency, [Hz]
Train and excavator bucket hits	4.434
Train	3.906

The analysis of the frequencies displayed in Tables 3 and 4 underlines that for excitation sources with higher vibrations the value of the frequencies are more reduced.

The speed of the truck was another significant factor in the analysis. It can be noticed that for a high moving speed, of 40 km/h, the frequency is also high, 6.11 Hz in the first mode and 19.60 Hz in the second mode. At a speed of 30 km/h the frequency is 5.44 Hz and 18.95 Hz respectively. Thus the frequency decreases when the speed of the truck is reduced.

The signal used for identification is recorded after the truck exists the bridge so the influence from the truck mass is avoided.

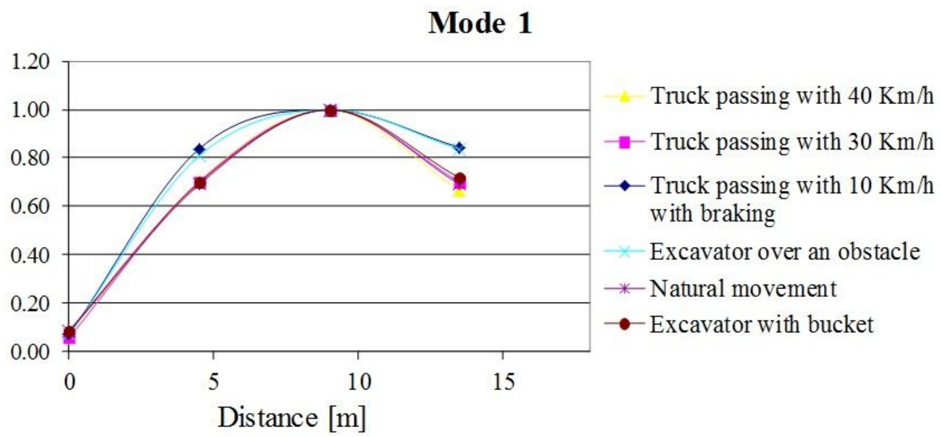


Fig. 8 – Mode 1, mode shapes on the vertical direction.

The shapes of the vibration modes have been normalized to unit value for analysis and comparison reasons, Figs. 8,...,10.

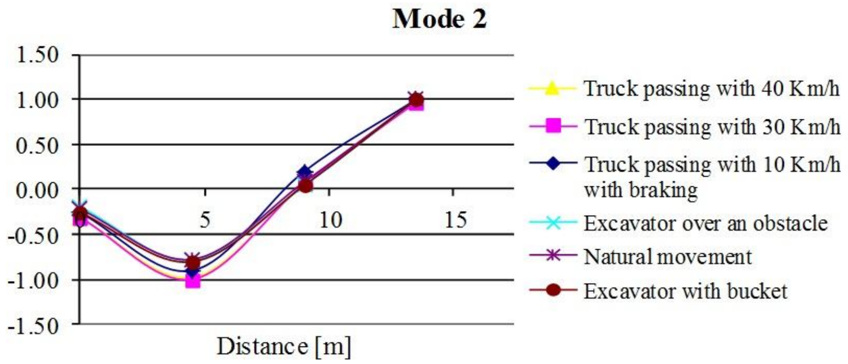


Fig. 9 – Mode 2, mode shapes on the vertical direction.

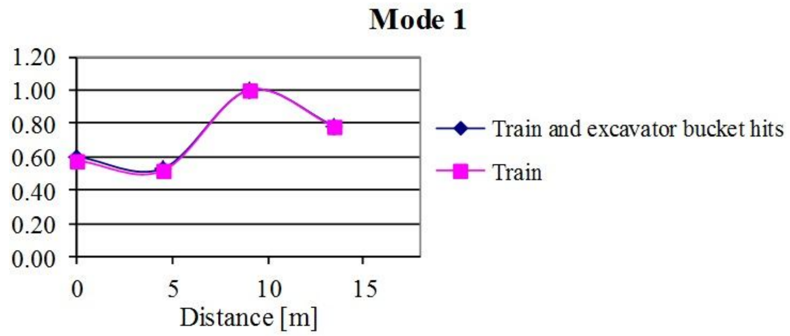


Fig. 10 – Mode 1, mode shapes on the horizontal direction.

4. Conclusions

Analysing the shapes of the vibration modes it can be stated that for a higher level of vibrations the modal coordinates are higher with respect to the ones measured at low vibrations (from the environment).

At high vibrations the stiffness of the structure is more reduced, fact proven through the comparison of the vibration frequencies. At a lower level of vibrations the structure behaves elastically and the non-bearing elements increase its stiffness.

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COMPARAREA CARACTERISTICILOR DINAMICE DETERMINATE EXPERIMENTAL ALE UNUI POD LA VIBRAŢII DIN MEDIU ŞI VIBRAŢII FORŢATE

(Rezumat)

Este prezintat un studiu de caz realizat pe un pod peste Dunăre, amplasat în localitatea Cernavodă, România. Structura testată a fost supusă unor vibraţii, din mişcarea naturală a podului şi din mişcarea unui camion, a unui tren şi a unui excavator. Sistemul de monitorizare folosit pentru înregistrarea datelor in situ a presupus amplasarea a 4 traductori seismici în prima deschidere a podului. Integrarea vitezelor şi identificarea modurilor de vibraţie au fost făcute cu ajutorul programului ARTeMIS Extractor. Accentul este pus pe analizarea formelor modale şi pe observarea relaţiei dintre frecvenţă şi ordonatele modale.