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CHARACTERIZATION OF BEARINGS NONLINEARITIES INFLUENCES ON VIADUCTS DYNAMIC RESPONSES

PhD. Eng. Adrian LEOPA, PhD. Eng. Silviu NASTAC
"Dunarea de Jos" University of Galati,
Research Center for Mechanics of Machines
and Technological Equipments

ABSTRACT

In view of viaducts designing and safety exploitation it is necessary to evaluate both theoretically, and instrumentally the dynamic behaviour for impulsive external actions. In this study the dynamic response for a singular bridge section was analyzed. There were considered only two degrees of freedom and the impulsive perturbations derived from the serviceable instrumental tests performed for this kind of construction objective at its commissioning.

KEYWORDS: viaduct, dynamic response, bearings, vibration, nonlinear vibration

1. INTRODUCTION

For a bridge or viaduct commissioning it had to be performed a succession of instrumental tests from the static and dynamic points of view. The dynamic tests have a purpose to evaluate the dynamic response parameters framing for a certain bridge or viaduct structure into the regulated range of values for this kind of constructions. Periodic evaluation of these parameters and their comparative analysis constitute an efficient method for damages identification which can appears both on the structure, and on the bearings. On other words the structural damages and the bearings failures will be identified through a nonlinear behaviour emergence for some essential dynamic response parameters [1].

For this analysis was proposed a complex physical and mathematical model. Based on this model it was demonstrates that the wearing out emergence into the bridge section bearings and implicitly the nonlinear behaviour of the resistant forces generated in these lead to qualitative and quantitative modifications of the dynamic response parameters of the base structure. At international level a great attention is offered to identification and to quantification of a bridge failure, but with hydraulics dampers mounted on sections supports. This is a modern and efficient technique for bridge damaging management and such an algorithm was successfully applied for structural integrity qualification of *Vincent Thomas Bridge* in Los Angeles [2].

2. DESCRIPTION OF DECK BRIDGE SYSTEM

Avoiding destructive effects on the viaducts due to the dynamic actions derived from earthquakes or road traffic can be done by different types of passive systems for dynamic insulation. Such a category is described by visco-elastic passive systems like the laminated rubber bearings.

This kind of dynamic isolation systems was used as insulation devices for sections on bridge piles, for the viaduct of Transylvania A3 highway in Romania placed at 29+602.75 ↔ 29+801.25 km (at Săvădisla, between Târgu Mureş and Cluj Napoca cities) [3]. Due to seismic actions, road traffic and environmental factors the rubber base materials have changed their properties in time which also to modifications of bridge dynamic response to impulsive external excitations. Hereby it is necessary to replace the insulation systems in order to avoid the partial or total demotion of the base structure of the bridge.

This study presents an evaluation methodology for the ordinary working state of a viaduct bearing systems based on the following suppositions as follows

- achievement of the predictive maintenance of anti-seismic systems which enables their changing at a right moment;
- post-seismic diagnosis of anti-seismic systems based on their dynamic response at impulsive actions [4].

The viaduct infrastructure consists of two sections and four piles for each direction of traffic (see Fig.1). The viaduct superstructure is transversely composed of four "U" type beams preformed and disposed at 3.32 m from each other (between their longitudinal axes). Over these beams it was applied a concrete super-slab of 25 cm thickness. The beams material was pre-casting reinforced concrete of C35/45 class, and the super-slab material was C25/30 class reinforced concrete. The viaduct has five sections each of 40 m length. The global insulation of the superstructure onto infrastructure, sections and piles elements was ensured with Freyssinet© type rubber bearings of 81 mm height.

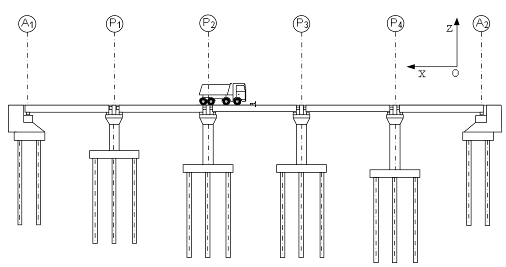

Fig. 1. The viaduct longitudinal profile

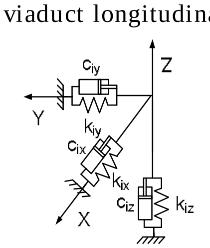

Fig. 2. Spatial orthogonal visco-elastic bearing

The study presented in this paper has evaluated and quantified the dynamic response of the viaduct section between P2 and P3 piles for a truck tip passing over a regulated bump according to SR12504/86 - Superstructures testing with trial actions. This configuration was based on the hypothesis according to which the proposed section has an independent movement compared to the other because of its free ends.

The infrastructure of the analyzed section is insulated on 16 visco-elastic elements with spatial orthogonal distribution such as the model in Fig. 2.

3. PHYSICAL AND MATHEMATICAL MODEL

For the physical and mathematical computational modeling of mechanical system subjected to external dynamic actions it is very important an appropriate defining of the excitation impulsive functions in respect with the shape, magnitude and time length of their effective application.

According to SR12504/86, the bridge section was tested with impulsive force generated by a truck tip with four axles and 41 tones total mass passing with 20 km/h over a bump of 40 mm regulated height (see Fig.3).

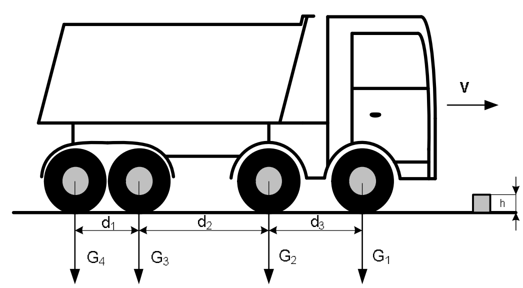

Fig. 3. The truck tip model for dynamic instrumental testing

The parameters in Fig. 4 have the following values: m_1= 7440 kg, m_2= 7339 kg, m_3= 13149 kg, m_4=13149kg, d_1= 1.5 m, d_2= 2.5 m, d_3= 2.0 m, h= 40 mm.

The percussion forces were evaluated with the mathematic expression as follows [5]

$$F_y = \frac{m v_0}{3\Delta t}\frac{h}{R}\left(2\frac{h}{R} - 5\right) \qquad (1)$$

where

h=0.04 m is the bump height, R=1.2 m denotes the wheel diameter, Δt=0.03s is the duration of the bump over passing; m denotes the mass distributed on the axle; v_0=20 km/h is the truck tip velocity at the bump over passing. The excitation forces due to the bump over passing for each axle have the following values:

$F_{y1}=1.4751\cdot10^5$ N;

$F_{y2}=1.4551\cdot10^5$N;

$F_{y3}=2.6071\cdot10^5$N;

$F_{y4}=2.6071\cdot10^5$N.

Supposing that the excitation function has an approximate rectangular shape, the global external action on the bridge section is composed by a succession of four rectangular pulses such as in diagram depicted in Fig. 4.

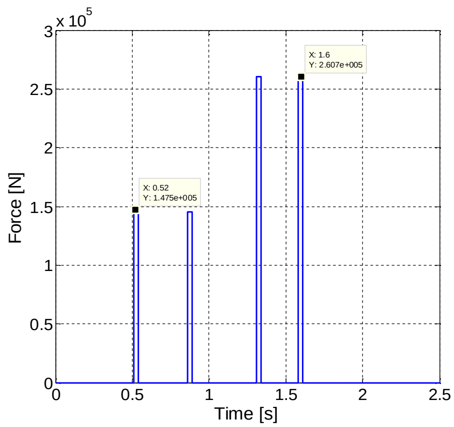

Fig. 4. Four rectangular pulses excitation signal

In view of physical model assembling the bridge section was treated such as a rigid body insulated on 16 visco-elastic spatial orthogonal elements - see model in Fig. 5.

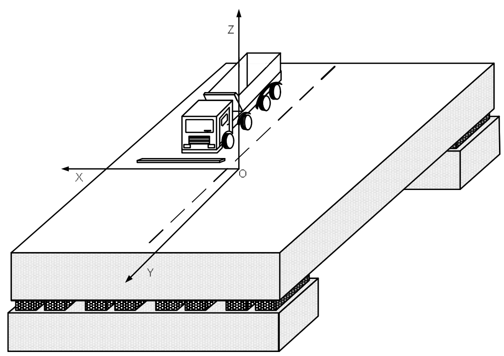

Fig. 5. The schematic diagram of the viaduct section model with external excitation system and neoprene bearings

The general expression of the oscillating movement system equation can be written as follows [6]

$$\underline{\underline{I}}\,\underline{\underline{\ddot{q}}} + \underline{\underline{C}}\,\underline{\underline{\dot{q}}} + \underline{\underline{K}}\,\underline{\underline{q}} = \underline{\underline{f}} \tag{2}$$

where

$\underline{\underline{q}}$ denotes the generalized coordinates vector;

$\underline{\underline{\dot{q}}}$ is the generalized velocities vector;

$\underline{\underline{\ddot{q}}}$ denotes the generalized accelerations vector;

$\underline{\underline{f}}$ denotes the generalized forces vector;

$\underline{I}$ is the matrix of inertial terms;

$\underline{C}$ denotes damping terms matrix;

$\underline{K}$ is the rigidity matrix.

The principal elastic axis of the elastic bearings is in parallel with the reference axis. In this case the movements due to coordinates variations according to the six degrees of freedom become uncoupled as follows:

- the coupled translation along the X axis and the rotational around the Y axis movements (X, φ_y);
- the coupled translation along the Y axis and the rotational around the X axis movements (Y, φ_x);
- the translation movement along the Z axis independent of the other modes;
- the rotational movement around the Z (φ_z) axis independent of the other modes.

In this case, the differential equations system can be structured as follows

- Coupled mode (X, φ_y)

$$\begin{cases} m\ddot{X} + \dot{X}\sum_{1}^{16} c_{ix} + \dot{\phi}_y \sum_{1}^{16} z_i c_{ix} + X\sum_{1}^{16} k_{ix} + \\ +\phi_y \sum_{1}^{16} z_i k_{ix} = 0 \\ J_y\ddot{\phi}_y + \dot{X}\sum_{1}^{16} z_i c_{ix} + \dot{\phi}_y \sum_{1}^{16}\left(c_{iz}x_i^2 + c_{ix}z_i^2\right) + \\ +X\sum_{1}^{16} z_i k_{ix} + \phi_y \sum_{1}^{16}\left(k_z x_i^2 + k_x z_i^2\right) = e_x F_z \end{cases} \tag{3}$$

- Coupled mode (Y, φ_x)

$$\begin{cases} m\ddot{Y} + \dot{Y}\sum_{1}^{16} c_{iy} - \dot{\phi}_x \sum_{1}^{16} c_{iy} z_i + Y\sum_{1}^{16} k_{iy} - \\ -\phi_x \sum_{1}^{16} k_{iy} z_i = 0 \\ J_x\ddot{\phi}_x - \dot{Y}\sum_{1}^{16} z_i c_{iy} + \dot{\phi}_x \sum_{1}^{16}\left(c_{iy}z_i^2 + c_{iz}y_i^2\right) - \\ -Y\sum_{1}^{16} z_i k_{iy} + \phi_x \sum_{1}^{16}\left(k_{iy} z_i^2 + k_{iz} y_i^2\right) = -e_y F_y \end{cases} \tag{4}$$

- Translation along the OZ axis

$$m\ddot{Z} + \dot{Z}\sum_{1}^{16} c_{iz} + Z\sum_{1}^{16} k_{iz} = -F_z \tag{5}$$

- Rotation around the OZ axis

$$\begin{gathered} J_z\ddot{\phi}_z + \dot{\phi}_z \sum_{1}^{16}\left(c_{ix}y_i^2 + 2c_{iy}x_i^2\right) + \\ +\phi_z \sum_{1}^{16}\left(k_{ix}y_i^2 + 2k_{iy}x_i^2\right) = 0 \end{gathered} \tag{6}$$

where

m is the deck bridge mass;

c_{iz} denotes the damping coefficient of bearing i on vertical direction;

k_{iz} is the rigidity coefficient of bearing i on vertical direction;

X, Y, Z denote deck bridge displacements on OX, OY and OZ directions;

ϕ_x, ϕ_y denote the mass *m* rotation movements around OX and OY axes;

x_i, y_i and z_i represent the bearings coordinates;

J_x, J_y , J_z - are the principal moments of inertia;

e_x and e_y denote the coordinates of the excitation force point of application measured for the mass center of the deck bridge; F_z, F_y denote the excitation forces.

4. THE DECK BRIDGE DYNAMIC RESPONSES OF FORWARD AND ROCKING MOVEMENTS COUPLED MODES

The differential equations system (4) was numerically solved in MatlabR14© software and were analyzed the following parameters of the deck bridge vibratory movement as follows:

- the displacement along OY direction in time and frequency domains;
- the acceleration along OY direction in time and frequency domains;
- acceleration spectrogram;
- movement stability through phases domain graphical analysis.

These parameters were comparatively analyzed for two distinctive cases as follows:

- elastic forces along OY direction having linear evolution;
- elastic forces along OY direction having nonlinear evolution with the following displacement dependence expression.

$$F_y = Y(1+\beta Y^2)\sum_{1}^{16} k_{iy} \qquad (1)$$

where $\beta=5\cdot10^8$ 1/m^2; $k_{iy}=3.15\cdot10^6$ N/m; $c_{iy}=2.5\cdot10^5$ Ns/m; $m=992\cdot10^3$ kg; $k_{iz}=650\cdot10^6$ N/m; $c_{iz}=2.5\cdot10^6$ Ns/m; $m=992\cdot10^3$ kg; $Jx=120.533\cdot10^6$ kgm^2; e_y=2m.

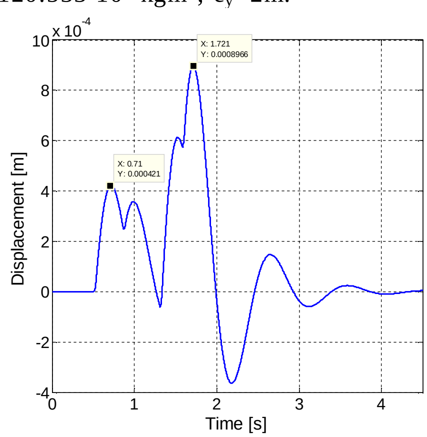

Fig. 6. Displacement of mass *m*: linear case

For the nonlinear case (see Fig. 7) it result a decreasing of displacement value to $2.9\cdot10^{-4}$ m compared to $8.9\cdot10^{-4}$ m for the linear case (see Fig. 6). This reduction results from the bearings rubber reinforcement due to ageing phenomenon. From the qualitative point of view it has to be pointed out the distorted shape of displacement for the nonlinear case compared to with the linear one.

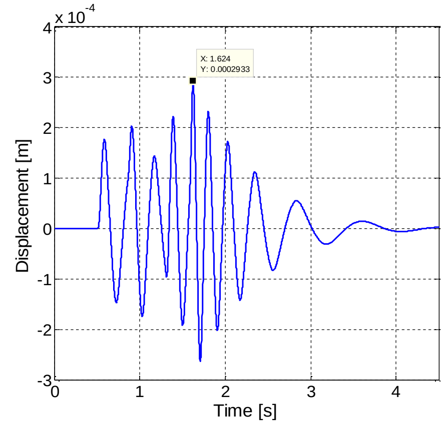

Fig. 7. Displacement of mass *m*: nonlinear case

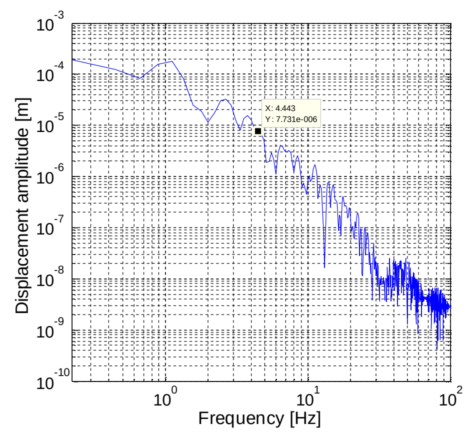

Fig. 8. Spectral composition of displacement in linear case

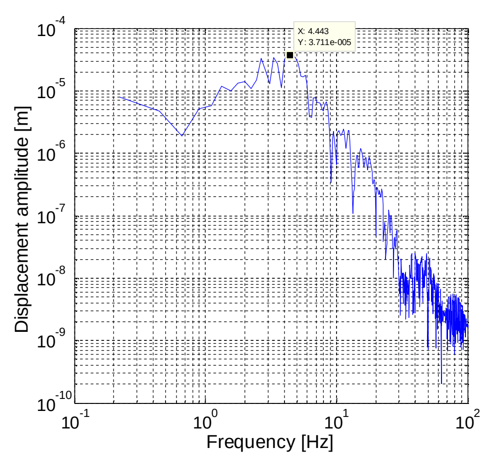

Fig. 9. Spectral composition of displacement in nonlinear case

From the frequency domain diagrams (see Fig. 8 and Fig. 9) of displacement parameter evolution, it results that nonlinearity imposes a shifting to the high frequencies of significant spectral components comparative to the linear case analysis. Hereby for the nonlinear case the significant spectral area is centered on 4.44 Hz value while for the linear case this area is found around 0.5 Hz value.

Analyzing the acceleration diagrams depicted in Fig. 10 and Fig. 11 taking into account the qualitative point of view, it results a decreasing of acceleration magnitude to $0.04 m/s^2$ in the nonlinear case comparative to $0.05 m/s^2$ for the linear case. Also, the shape of the acceleration signal is very much distorted for nonlinear case compared to linear case.

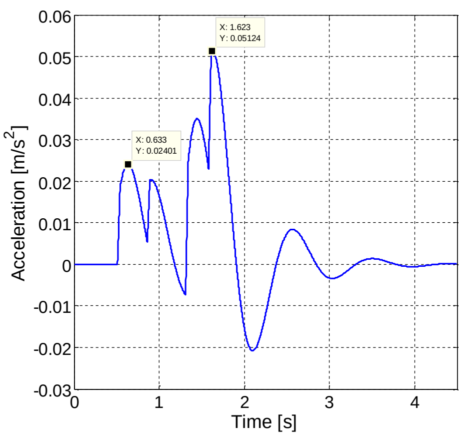

Fig. 10. Acceleration magnitude of mass *m* – linear case

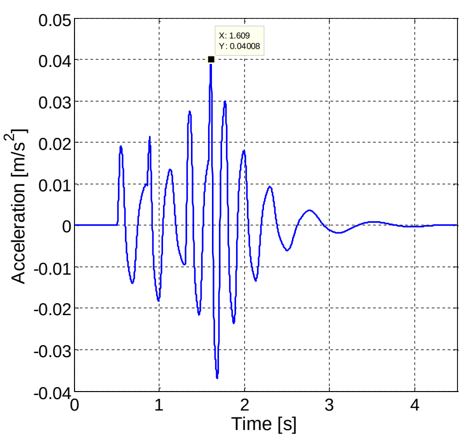

Fig. 11. Acceleration magnitude of mass *m* – nonlinear case

Spectral composition of acceleration signals depicted in diagrams in Fig. 12 and Fig. 13 also reveals a right side shifting to high frequencies of significant component area such as the displacements case. Hereby for the nonlinear case the central value or significant components area is 4.22 Hz while for linear case this value is around 0.5 Hz.

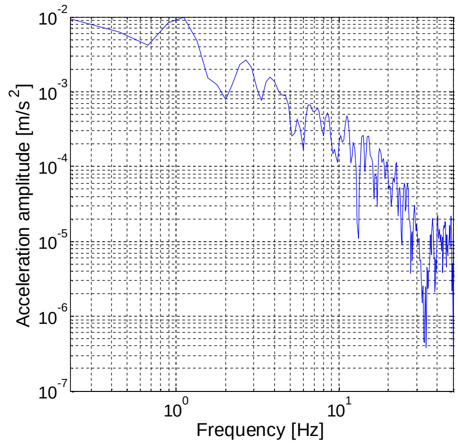

Fig. 12. Spectral composition of acceleration in linear case

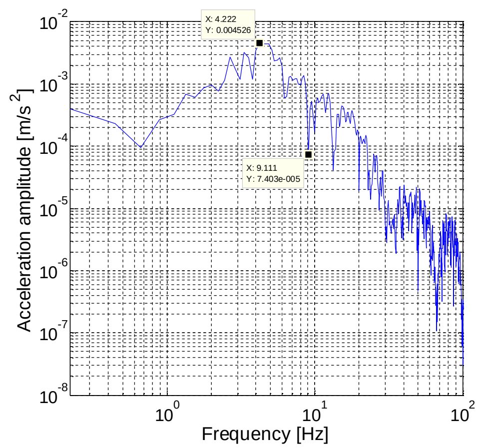

Fig. 13. Spectral composition of acceleration in nonlinear case

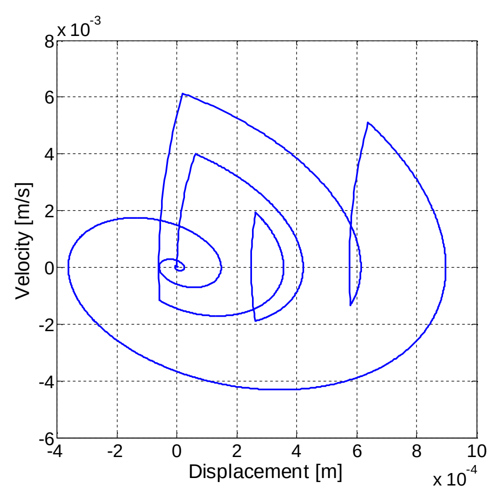

Fig. 14. Phase domain diagram: linear case

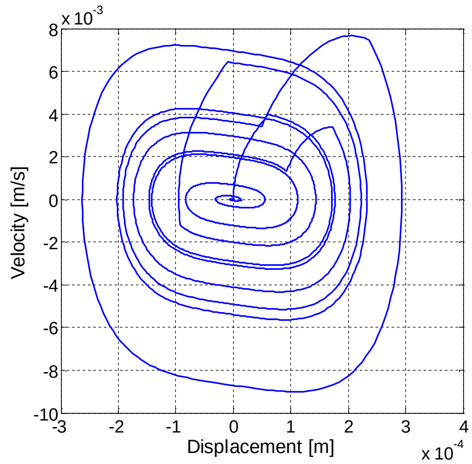

Fig. 15. Phase domain diagram: nonlinear case

Graphical representation of displacement - velocity dependence constitutes a valuable indication of the system stability evolution. From the diagrams depicted in Fig. 14 and Fig. 15 it results that system evolution has a stable character for both cases (linear and nonlinear). The differences only have the qualitative character showing the strong dynamics of the nonlinear case versus the linear one.

5. CONCLUSION

This study demonstrates the influences of the nonlinear behaviour of the rubber-based bearings on the deck bridge dynamic response in case of road traffic impulsive excitations. Based on the theoretical model proposed and presented in this paper it can be elaborated a regular method intended for the predictive maintenance of the ordinary working state of the rubber-based bearings. This method can contain the following steps as follows

- At commissioning to action of the viaduct, when dynamic insulation systems are new and, accordingly, it can be supposed to have a linear behaviour characteristic, there will be done instrumental tests based on which it will be evaluated a set of reference parameters of the bridge dynamics.
- After a certain time period of ordinary utilization of the viaduct, the experimental tests will be repeated for the same conditions and hypothesis like the managing to action time; through this analysis it has to be carried out the quantitative and qualitative characterization of the modification in evolution of the reference parameters.
- Based on the two sets of values for the reference parameters, it can be performed a comparative analysis with the final purpose of pointing out the differences between them; hereby the possible differences which will be identified and quantified highlighted the damages of the visco-elastic insulation devices and the emergence of their failure state.

These correlations between the nonlinear behaviour of the elastic component of rubber-based bearings and the modifications which appear into the structure dynamic response were only theoretically analysed, but this study opens the opportunity of the "in situ" instrumental testing of this analytical approach.

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