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JOURNAL OF CIVIL ENGINEERING AND MANAGEMENT
ISSN 1392-3730 print/ISSN 1822-3605 online
2011 Volume 17(4): 590–599
http://dx.doi.org/10.3846/13923730.2011.632489

MODAL ANALYSIS OF BRIDGE STRUCTURES BY MEANS OF FORCED VIBRATION TESTS

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Received 23 Aug. 2011; accepted 11 Oct. 2011

Abstract. New modern bridges and older structures exposed to accelerated deterioration need permanent condition monitoring. The major tools used in bridge condition evaluation are based on the results of the experimental modal analysis of bridge structures. This paper focuses on the methodology of Forced Vibration Tests performed by means of mechanical exciters. A comprehensive testing system called MANABRIS, developed at Wrocław University of Technology, is presented. The system is equipped with a rotational eccentric mass exciter and dedicated software for programming and controlling the tests and for acquiring and processing measurement data. The results of a Forced Vibration Test carried out on a typical railway bridge are compared with the results of a conventional modal test of the structure excited by trains. The precision of the considered testing techniques is evaluated and the range of their effective application is proposed.

Keywords: bridge, dynamics, modal analysis, exciter, vibration test, field test.

1. Introduction

The transport network of each developed country belongs to the busiest and most heavily exploited systems. Bridges are the most critical points in this network and due to their peculiar structure and intensive use they are exposed to accelerated deterioration. The existing, progressively ageing, bridge structures are continually subjected to various dynamic loads, e.g. moving live loads, time-varying wind loads, ground vibrations, etc., as well as to other degradation processes (e.g. Alampalli 2000; Bień 2010; Olofsson *et al.* 2005). On the other hand, recent trends are forcing engineers to design and construct more and more daring and slender structures, whereby new dynamic phenomena appear in bridge behaviour. As a result, the interest in the experimental dynamic testing of bridges and in developing new bridge dynamic analysis tools grows (e.g. Alampalli 2000; Brincker *et al.* 2003; Bryja 2009; Cunha *et al.* 2007; Doebling *et al.* 1996; Gładysz, Śniady 2009; Maia *et al.* 2003; Wenzel, Pichler 2005).

One of the most promising techniques of experimental dynamics is the Classical Modal Analysis (CMA) based on the Forced Vibration Test (e.g. Bień *et al.* 2006; Ewins 2000; Skoczyński *et al.* 2006, 2009; Zwolski 2007). Through such an experimental modal analysis one can determine the natural vibration frequencies, the corresponding mode shapes and the damping characteristics of bridges. Bridge modal parameters, based on the results of forced vibration tests, form the foundation for the following applications:

- the evaluation of bridge condition (conformity with the design dynamic parameters, serviceability, dynamic sensitivity, user comfort, etc.);
- the updating of theoretical bridge structure models;
- the detection of structural defects manifesting themselves in changes in the dynamic characteristics;
- the monitoring of bridge condition through the systematic control of the structure's dynamic parameters;
- the optimization of bridge infrastructure management.

The Forced Vibration Test technique has been developed in close (decade-long) collaboration between the Institute of Civil Engineering and the Institute of Production Engineering and Automation, both at Wrocław University of Technology. The system has been successfully used in the dynamic testing of over 10 bridge structures (e.g. Bień *et al.* 2004; Skoczyński *et al.* 2006, 2009; Zwolski 2007). The results of the theoretical and experimental research on the Forced Vibration Test have been included in international recommendations (Guideline 2008).

2. Classification of bridge dynamic tests

In the classification of bridge dynamic tests, two main types of such tests can be distinguished (Fig. 1):

- Operational Tests – the identification of the vibration parameters of a structure subjected to a specific load;
- Modal Tests – the identification of the parameters of the vibrating bridge structure itself, which are independent of the type of excitation.

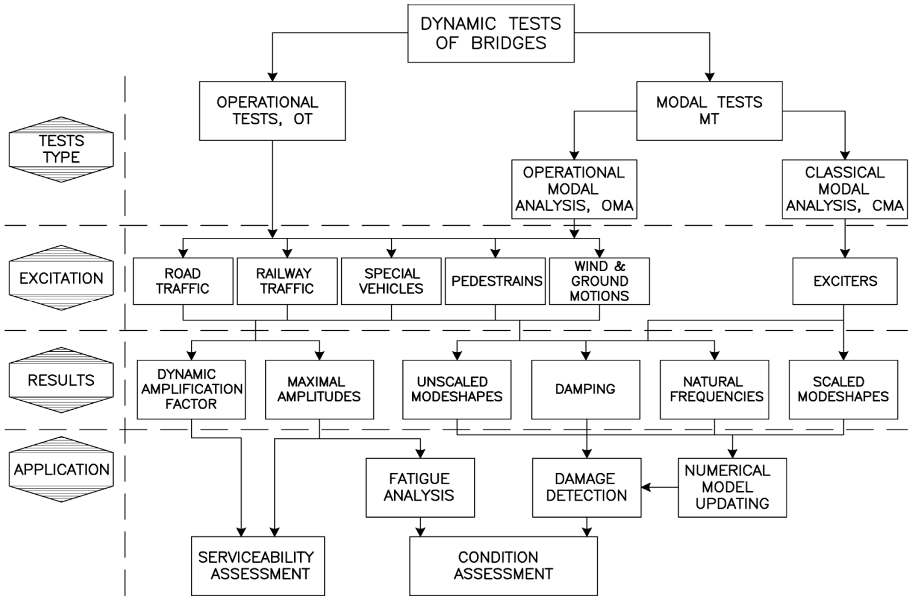

Fig. 1. Dynamic tests of bridges – types of tests, excitation techniques, obtained modal parameters and their applications

Operational Tests (OT) usually use typical traffic (vehicles, trains, pedestrians) or ambient (wind, ground motions) excitations to identify the response of the structure to a specific dynamic load. The measured data supply information on the vibration parameters of the whole structure-vehicle system. The results of road and pedestrian bridge tests are unique owing to such system-specific parameters as car suspension, axle load, velocity, crossing route and so on. In the case of railway bridge tests in which special trains are used, the repeatability of results for the same load scheme is even better.

Modal Tests (MT) can be performed in two ways: using immeasurable forces generated by traffic or wind (Operational Modal Analysis (OMA)) as excitation or using special exciters with force measuring instrumentation (Classical Modal Analysis (CMA)). CMA results supply information on the natural frequencies, scaled mode shapes and modal damping coefficients of the tested structure. The applied excitation does not affect the tested structure's mass or stiffness whereby the obtained results reflect the performance of the "pure" structure. An exciter (sometimes referred to as a shaker) is a mechanical device generating vibration with controlled parameters and enabling the measurement of the exciting force in the course of the experiment. The measured excitation forces and the responses of the structure are used for determining the Frequency Response Functions (FRF) and for estimating a modal model of the structure by applying a selected curve-fit procedure (e.g. Ewins 2000; Maia *et al.* 2003; Zwolski 2007).

OMA is a very useful alternative to CMA in the case of large structures such as long-span bridges which are difficult to excite with a shaker. Using OMA, one can obtain natural frequencies and modal damping coefficients, but the mode shapes cannot be mass-scaled because the excitation forces are unknown. The results of OMA can be more reliable when the following conditions are fulfilled:

- excitation has to be applied randomly, in terms of space and spread, to the whole structure;
- excitation has to be random in terms of frequency, and should last throughout the test.

In comparison with the CMA tests, the OMA techniques offer additional information required in the identification of the Dynamic Amplification Factor (DAF) and information on the maximum amplitudes of the dynamic displacements, strains, vibration velocity and acceleration caused by the applied loads. When normal traffic is used as excitation, the results of OMA are biased by the additional mass of the live load moving along the structure.

The dynamic parameters of a bridge structure can be identified on the basis of a single CMA or OMA test or they can be acquired either by permanently installed monitoring system (OMA) or through periodically performed CMA tests. The results of CMA tests are mainly used to assess the condition of the structure, including damage detection (e.g. Alampalli 2000; Doebling *et al.* 1996; Maia *et al.* 2003; Skoczyński *et al.* 2006, 2009; Zwolski 2007). This experimental technique is also very useful in the calibration of theoretical models of bridge structures. The results of OMA tests are particularly valuable for load capacity and fatigue analysis and bridge serviceability assessment (e.g. Bień *et al.* 2004; Hawryszków 2009; Zwolski 2007).

3. MANABRIS system

3.1. System conception

Taking into account the limitations of OMA, the MANABRIS system (Modal ANAlysis of BRIdge Structures) was developed as a comprehensive tool for the experimental modal analysis of bridge structures. The system is based on the following assumptions: independence from an external source of electric energy, portability, durability and resistance to outdoor conditions, modular structure, comprehensive control by a computer

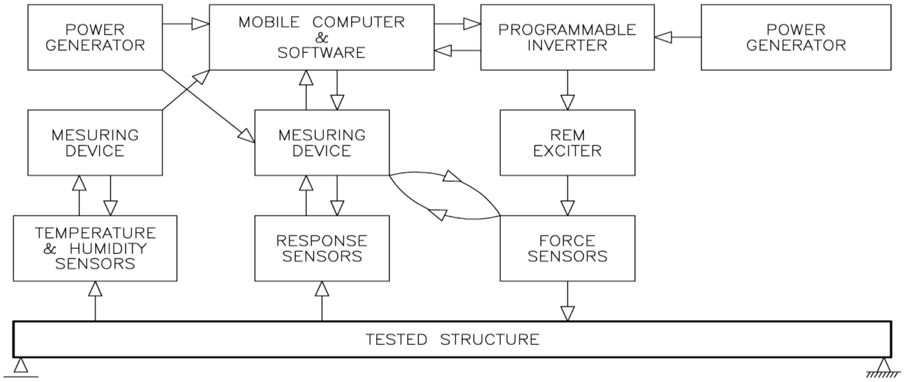

Fig. 2. Schematic of MANABRIS testing system architecture

and safety of the measured data. The system has an open structure enabling one to add new components such as test procedures, exciters, data acquisition devices, sensors and so on. The control software enables real-time data visualisation during the test and the preliminary processing of the recorded data.

The system was developed by a research team (Bień *et al.* 2006; Skoczyński *et al.* 2006, 2009; Zwolski 2007) from Wrocław University of Technology (WUT) and it consists of the following components (Fig. 2):

- a REM exciter with a programmable inverter and force sensors;
- a portable computer with the MANABRIS control software;
- a measuring device with response sensors;
- 2 portable power generators;
- a measuring device with temperature and humidity sensors.

Work on the MANBRIS system started within the framework of the Research Project 8TO7E/04020 "A method of the experimental identification of the dynamic characteristics of bridge structures using an inertial exciter" funded by the Polish State Committee for Scientific Research. Prototypes of the rotational eccentric mass (REM) exciter were designed and built. The work was continued internationally as part of the Integrated Research Project "Sustainable Bridges – Assessment for Future Traffic Demands and Longer Lives" (Olofsson *et al*. 2005) within the 6th Framework Programme of the European Union. The exciter design was improved to enable the testing of both road and railway bridges. Several laboratory tests of all the system components and pilot bridge tests were carried out to calibrate the method and to evaluate its practical usefulness and sensitivity to weather conditions (temperature, humidity, etc.).

3.2. Rotational eccentric mass exciter

The principle of operation of the exciter used in the MANABRIS system (Fig. 3) consists in generating an eccentric force by two masses rotating in opposite directions with the speed controlled by an electric motor. The motor is powered through an inverter which enables the precise control of rotational speed and excitation frequency. The inverter is powered by a portable power generator. The body of the exciter is equipped with detachable wheels for easy transport, but during the test it is supported by 3 load cells enabling excitation force measurement.

The exciter with special auxiliary equipment, consisting of a steel frame and a set of force sensors (also functioning as frame supports), can be used on both road bridges (Fig. 3) and railway bridges (Fig. 6a). In the latter case, the frame structure is attached to the rails by means of special clamping elements.

Fig. 3. Rotational eccentric mass exciter installed on road bridge

The exciter was tested in a laboratory in order to determine its parameters (the range of excitation frequency, the excitation force amplitude vs. frequency, the stability of the excitation force and frequency, etc.) and in field tests of over 10 bridge structures (Zwolski 2007). On this basis, software and hardware tools for dynamic bridge testing by means of mechanical exciters were developed and improved.

The rotational exciter can force vibrations in a range of 3–14 Hz and 3–30 Hz in respectively a road bridge and a railway bridge. The frequency range is wider in the latter case because the rails make it possible to fix the exciter firmly to the bridge and prevent its undesirable rise (jumping) at higher excitation frequencies. The frequency can be controlled with a resolution of 0.006 Hz, depending on the inverter used. The REM exciter can generate two types of force signal: a harmonic signal or a tuned frequency harmonic signal. The pure harmonic signal is used in the stepped sine test where the excitation frequency is constant in the consecutive steps. The tuned harmonic signal is used in sweep tests where the excitation frequency is continuously changed in a single test.

3.3. Control application

The control application has a modular structure and consists of the MANABRIS main control module working together with the DAPRO, MODEST and TEMODAN modules (Zwolski 2007).

The MANABRIS module serves the communication between the user and all the devices (exciters, data acquisition systems), and the setting of all the test parameters (location and types of sensors, excitation parameters, acquisition parameters, etc.). The module also controls the execution of tests with a predefined excitation signal, as well as the saving, inspecting and initial pre-processing of the acquired signal.

The DAPRO module is used for the processing of the raw measured signal in time domain to the final products, i.e. frequency response functions and coherence matrices, both expressed in frequency domain. The frequency response functions (FRF) are estimated using the following formula:

$$H_1(\omega) = \frac{G_{XF}(\omega)}{G_{FF}(\omega)}, \tag{1}$$

where: $H_1(\omega)$ is a FRF estimator; $G_{XF}(\omega)$ is the cross-spectrum of the measured displacement, velocity, acceleration or excitation force; $G_{FF}(\omega)$ is the auto-spectrum of the measured excitation force; ω is frequency.

For FRF estimation, spectra $G_{XF}(\omega)$ and $G_{FF}(\omega)$ are calculated (using the Fast Fourier Transform algorithm) from time domain signals, taking into account the averaged results from a few repetitions of the experiment. The FRF can be obtained from a sweep test where in a single experiment the structure is excited by a tuned harmonic signal within a preset frequency range. In this case, the FRF values calculated from formula (1) are valid for only the excitation frequency range.

FRF identification can also be performed at discrete frequencies by applying harmonic excitation at predefined frequencies and calculating the discrete values of FRF for each of the excitation frequencies. The procedure is called the Stepped Sine Test (SST) and it is generally considered to be a very precise, although a time-consuming, method.

The modal parameters of a bridge structure are estimated in the MODEST module. The program incorporates four SDOF curve-fitting algorithms: Peak Picking (PP), Circle Fit (CF), Line Fit (LF) and Direct Modal Estimation (DME) as well as two MDOF algorithms: Frequency Domain Decomposition by Peak Picking (FDD-PP) and its Enhanced version (EFDD). Details of the algorithms can be found in the literature (e.g. Ewins 2000; Maia *et al.* 2003). The DME method is a comprehensive name which Zwolski (2007) gave the simple time domain SDOF techniques for natural frequency estimation by the zero-crossing method and modal damping estimation by the logarithmic decrement method. Modal parameters are calculated in the MODEST module using standard deviation estimation and the identified mode shapes are presented against the background of the tested structure's geometry.

The TEMODAN module is used for the theoretical modal analysis of structures modelled by one-dimensional elements by means of the Finite Element Method and for comparing the numerically identified modal models with the ones estimated experimentally. The correlation analysis can be performed using all the modal parameters and their various derivatives: mode shape slopes and curvatures, the damage index (Maia *et al.* 2003), MAC – the Modal Assurance Criterion, and COMAC – the Coordinate Modal Assurance Criterion (Ewins 2000). The module also includes two correlation functions proposed by Zwolski (2007): UNCOMAC and MFAC (the Mode shape and Frequency Assurance Criterion). Function UNCOMAC is simply derived from the well known COMAC function for each degree of freedom (DOF) k, using the formula:

$$\text{UNCOMAC}_k = \left\| 1 - \text{COMAC}_k \right\|. \tag{2}$$

Thanks to this form of the correlation function its values can be displayed on the model mesh structure in relation to the translational degrees of freedom. The values form a shape of a "deformed" structure and the regions with maximum "deformation" values mark the location of uncorrelation.

The MFAC factor is derived from MAC, but it takes into account not only the mode shapes of the compared modal models, but also the natural frequencies, and it is expressed by the formula:

$$\text{MFAC} = \frac{1}{n}\sum_{r=1}^{n}\left(\text{MAC}_r \cdot \left(1 - \text{abs}\left(1 - \frac{f_r^t}{f_r^e}\right)\right)\right), \tag{3}$$

where: n – the number of modes in the modal model; MAC_r – values calculated from two models for coupled modes r; f_r^t – the natural frequency of mode r from the 1st model (e.g. a theoretical model); f_r^e – the natural frequency of mode r from the 2nd model (e.g. an experimental model).

The factor is calculated as a single value for the pair of models and it expresses the degree of their correlation.

The TEMODAN module also supports the efficient location of the sensors and the exciter through the calculation of the Reference Indicator (RI) from the formula:

$$\text{RI}_k = \left| \prod_{i=1}^{r} \phi_k \right|, \tag{4}$$

where: ϕ_k – eigenvectors; k – DOF's number; r – the number of modes taken into account.

The RI factor is based on the eigenvector values calculated for the numerical model of the structure using FEM. The values of this factor are presented on the structure mesh and they show regions of the structure where the response according to all the modes is high. Small (or zero) values of RI indicate regions where at least one mode has a zero value and where the location of sensors or the exciter is irrelevant. The name of the factor derives from the fact that the DOFs of the structure where RI has the highest values are the best candidates for locating the reference sensors during testing sessions involving many setups of the other sensors. The reference sensors are kept in the same locations in all the setups and the signal measured in these points is used to combine the responses from all the setups in order to determine mode shapes for the whole structure.

4. Comparison of OMA and CMA for railway bridge

4.1. OT and OMA test

In its development phase, the performance of the MANABRIS system had to be checked through modal tests on full-scale bridge structures. The tests had the following aims:

- to test the efficiency of the system in the field and its performance in various weather conditions;
- to evaluate the accuracy, execution time and limitations of the various testing methods;
- to compare the results of the application of various means of excitation to a typical railway structure with a ballasted track;
- to test the effectiveness of all the procedures and components implemented in the MANABRIS system during testing and data processing in real field conditions.

Three testing methods, i.e. Operational Tests and Operational Modal Analysis carried out using freight trains, and Classical Modal Analysis performed using the MANABRIS system, were employed. It was anticipated that the structure's modal parameters identified at the operational excitation would differ from the ones identified at the forced excitation not only in terms of estimated values, but also in terms of accuracy.

A typical medium-span railway bridge (Fig. 4) was chosen for the tests. The bridge (general view in Fig. 4a) crosses the Ślęza River in Wrocław, Poland. The bridge carries a single standard-gauge track laid on a layer of ballast. The structure is a simply supported span of 31 m consisting of two steel plate girders with inclined webs and a orthotropic steel deck. The superstructure height is 1.30 m. The axes of the supports are oblique to the longitudinal axis of the structure, with the skew amounting to 51°. The viaduct rests on two massive concrete abutments.

The location of the measuring points during the tests is shown in Fig. 4b. Four B12/200 type accelerometers, made by Hottinger Baldwin Messtechnik, and four LVDT sensors for displacement measurement (also made by HBM) were used to measure the response signal.

First the bridge was tested under freight trains crossing it at a constant speed of about 40 km/h. In the course of the tests, five crossings by different trains were recorded. A typical signal from accelerometer A02, acquired during a train crossing is shown in Fig. 5a. Three vibration history phases can be distinguished in this signal: a forced vibration phase when the train is crossing the bridge, a free vibration phase after the train has crossed the bridge and a noise phase when the excited vibrations are fading. The autospectra were calculated separately for the forced vibration part and separately for the free vibration + noise part of the signal and then the autospectra were averaged for 5 train crossings (Fig. 5b). For comparison purposes the averaged spectra were normalized relative to the maximum value, even though the signals acquired during the train crossings carry much more energy than the ones acquired during the free vibration phase.

a)

b)

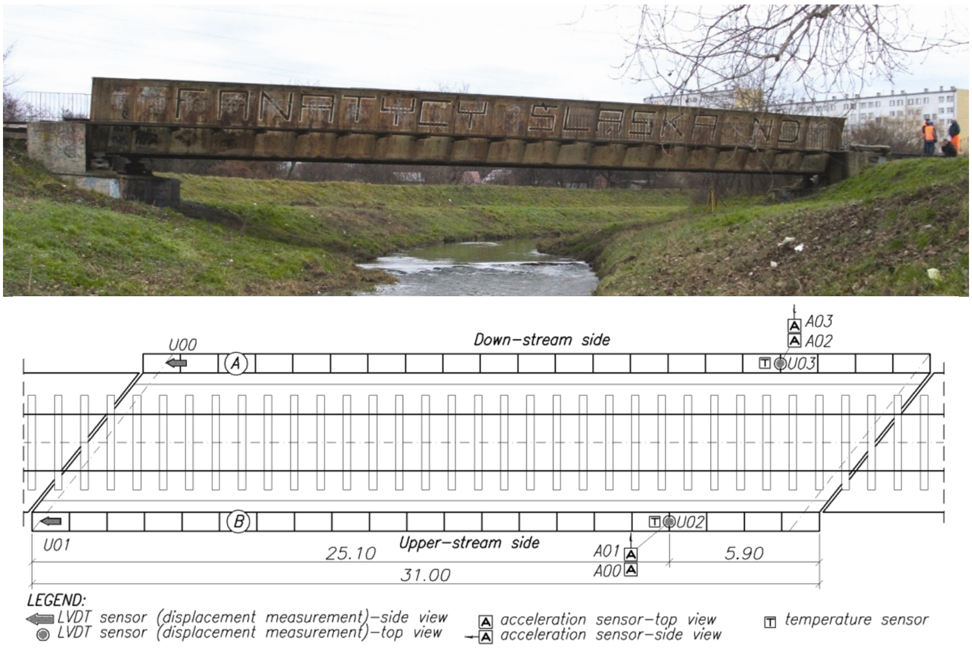

Fig. 4. Bridge under OT and OMA: a) general view;
b) bridge dimensions and location of measuring points

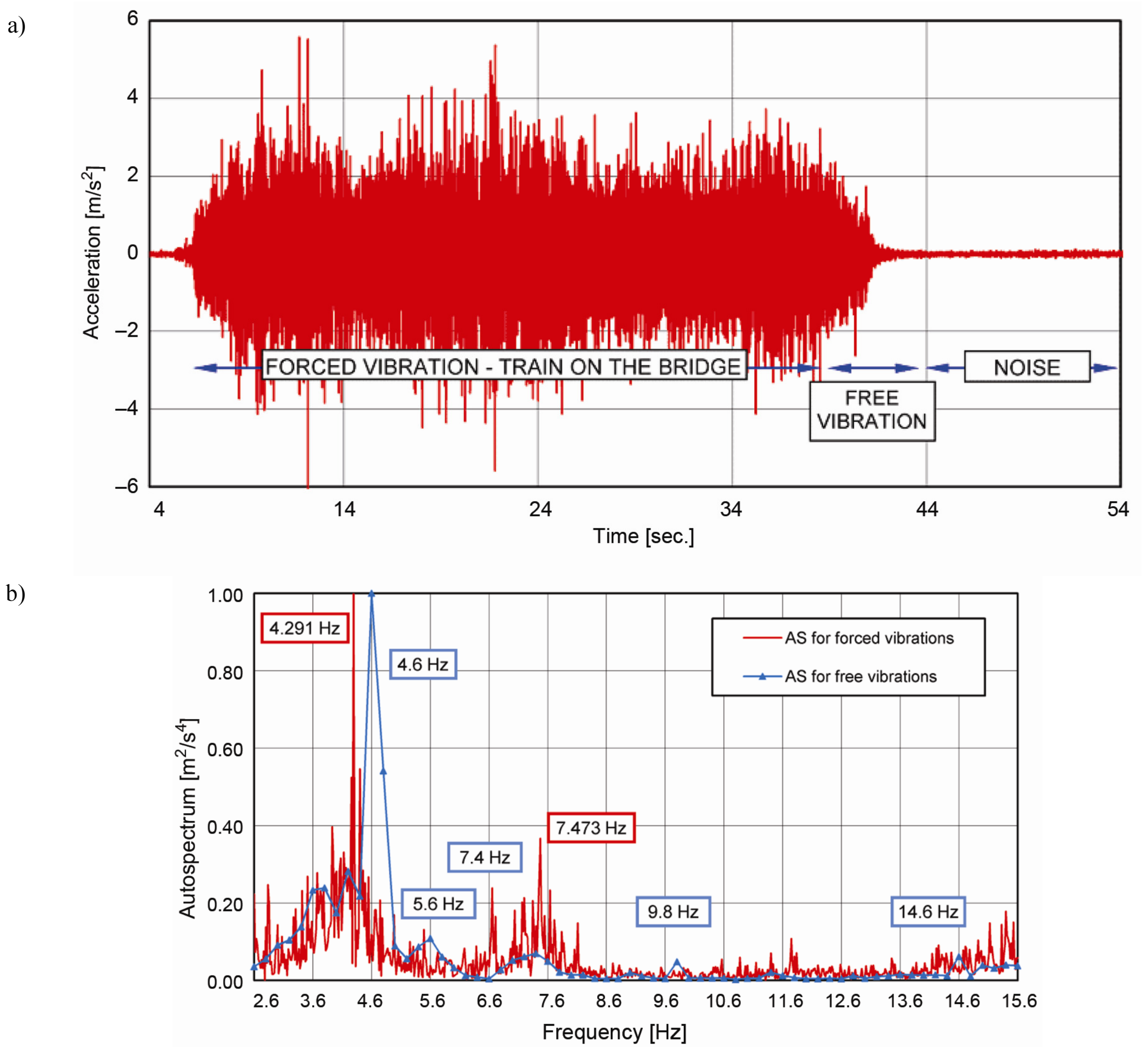

Fig. 5. Results for train crossings for signal from sensor A02: a) acceleration; b) autospectra for respectively forced and free vibrations

A comparison of the two spectrum functions revealed the following differences:

- the resolution of the two functions is different, which is due to the different signal acquisition times, i.e. 55 s for the train crossing and 5 s for the free vibration phase;
- the location of the peaks relative to the frequency axis indicates that the two spectra differ in the amount of vibration energy. The structure loaded by the additional mass of the train vibrates with other (most often with lower) frequencies than during the free vibration phase, which is most visible in the case of the frequencies: 4.291 Hz (forced vibration) and 4.6 Hz (free vibration);
- the noise in the case of forced vibration is more intensive due to the fact that the train is a source of many harmonic excitations.

The identification of mode shapes in OMA tests with train crossings would require recording the structure response in a gird of measuring points representative of the structure under numerous train crossings, which would be time-consuming because of the large number of sensors involved. Considering the short duration of the valuable signal remaining after a train crossing, the low resolution of the spectrum and the low signal-to-noise ratio, it was decided not to identify mode shapes by OMA for the analysed bridge.

4.2. CMA tests

Then the bridge was tested by means of the REM exciter located on the span as shown in Fig. 6. The exciter's supporting frame was attached to the bridge structure by means of the bow-shaped force sensors and special clamping elements fixed to the rails (Fig. 7).

The test programme was as follows:

- a test with exponentially tuned sweep excitation within the range of 3–24 Hz (acquisition time 212 s, three repetitions);
- a test with linearly tuned sweep excitation within the range of 3–24 Hz (acquisition time 317 s, two repetitions);
- a test with harmonic excitation stepped within the range of 3–13.2 Hz (the steps varied from 0.016 to 0.032 Hz and the acquisition time varied from 31 to 62 s).

a)

b)

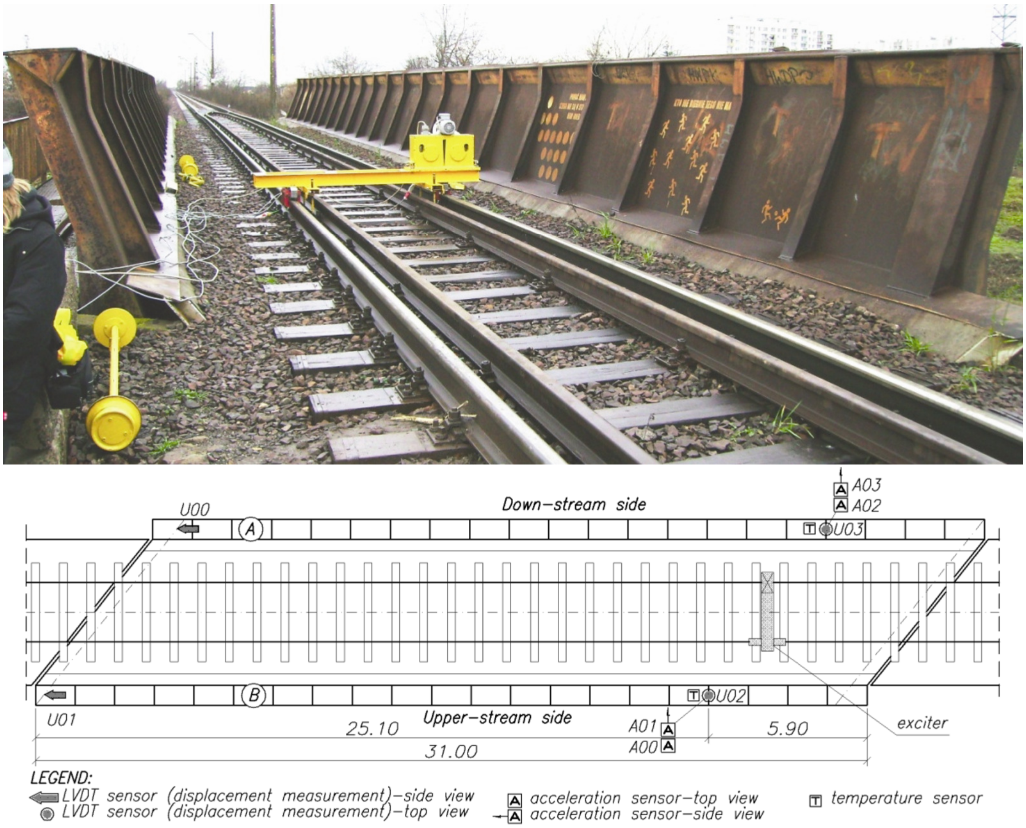

Fig. 6. Railway bridge under CMA: a) general view; b) location of measuring points and exciter

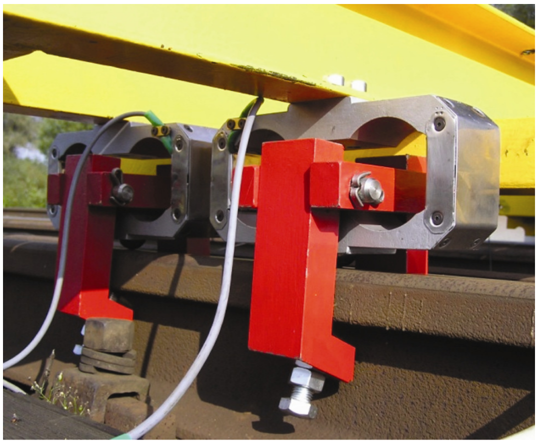

Fig. 7. Force sensors and clamping elements

The sampling frequency in all the OMA and CMA tests was set to 800 Hz. Since during the test both the exciting forces and the structure responses were recorded, the Frequency Response Functions were calculated using the H_1 estimator and averaged across the repetitions. An exemplary abs (FRF) obtained from the CMA test, together with the autospectra obtained from OMA tests based on signals recorded by accelerometer A02 are shown in Fig. 8.

The general shape of all the FRFs is similar and consistent. In the range of 3–15 Hz five modes were identified using Peak Picking, Circle Fit and Line Fit methods. The mean frequency and damping values for all the estimation methods are shown in Table 1.

The technique of harmonic excitations yields FRFs with the lowest noise content. In the FRFs obtained in the two sweep tests in the low-frequency range, noise is visible between the resonances. This is probably due to the low excitation energy of the rotational mass exciters, in the case of which the excitation force depends on the rotational frequency.

The noise could be eliminated in two ways: 1) by increasing the number of test repetitions and 2) by increasing the signal tuning time, i. e. the time in which the structure responds to consecutive excitation frequencies.

The FRFs obtained in the sweep tests have the highest resolution, i.e. 0.0047 Hz at exponential tuning and 0.0032 Hz at linear tuning.

Table 1. Comparison of frequencies identified by OT, OMA and CMA

Mode No.	OT	OMA	CMA				
	PP		*PP*	*CF*		*LF*	
	f_r [Hz]		f_r [Hz]	$\hat{f}_r$ [Hz]	$\hat{\zeta}_r$ [%]	$\hat{f}_r$ [Hz]	$\hat{\zeta}_r$ [%]
1	–	4.2	4.030	–	–	4.027	1.1
2	4.291	4.6	4.677	4.656	1.0	4.689	1.0
3	–	–	9.030	8.965	3.9	8.874	5.0
4	–	–	11.613	11.647	3.9	11.622	3.8
5	–	14.6	14.557	14.508	2.5	14.511	2.1

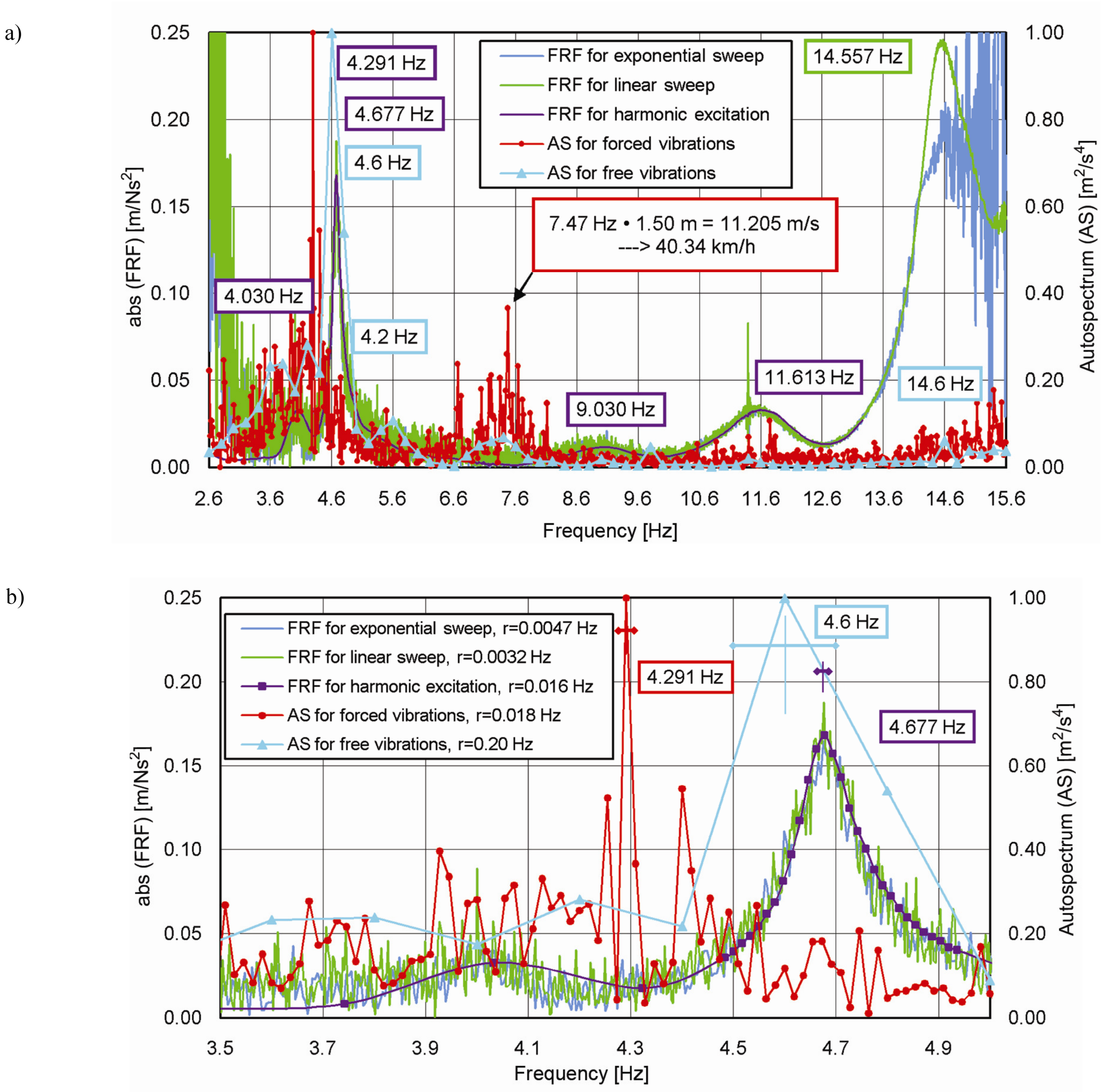

Fig. 8. Autospectra for OT and OMA tests with FRFs for all CMA tests based on signals acquired by accelerometer A02: a) whole range of analysis; b) resolutions (frequency range of 3.5–5.0 Hz)

The train crossings excited bridge vibrations in the low frequency range. The dominant frequency during a train crossing is 4.291 Hz and it is lower by 0.386 Hz (9%) than the resonant frequency identified from the FRFs. The dominant natural frequency identified from the free vibration test is 4.6 Hz, which agrees quite well with the CMA results, except for the very low (0.2 Hz) estimation accuracy (the resolution of the function).

In the range of 6.6–8.0 Hz, a few peaks, which are not present in the FRFs, occur in the autospectrum. This can be explained by the excitation of the bridge by the bogies' wheels spaced at 1.5 m when the train is crossing the bridge at a speed of about 40 km/h. Because of their origin, the presence of the peaks in the spectrum disturbs the interpretation of the results to be used in a modal analysis focused on the identification of the parameters of the structure itself.

The total time of data acquisition in the course of the stepped harmonic test was about 2 hours. For the tests with tuned sweep excitation the time was about 11 min (approximately the same for both ways of tuning) while for the train crossings it amounted to about 5 min. Taking into account the times, the effectiveness of bridge modal parameters determination and the quite high damping identified for the tested structure, one can conclude that the exciter with a tuned sweep signal is the fastest and most reliable method of modal parameters identification.

Operational excitation in the modal testing of this bridge was found to be ineffective due to the very short free vibration fading time (about 1 s). Moreover, either the train crossings did not excite the structure modes with higher frequencies or the higher-frequency vibrations were quickly and effectively damped by the train itself. Other sources of excitations, like wind, were not taken into account since their energy is too low to excite vibrations in such a rigid bridge structure.

5. Conclusions

For the considered bridge the CMA results have been found to be more accurate and consistent than the OMA results. From the results of the Forced Vibration Tests carried out on over 10 bridge structures by means of the MANABRIS system one can draw the following conclusions:

- Thanks to the use of exciters in CMA on can control the amplitude, frequency and direction of the exciting force.
- Excitation with exciters can be repeated at the same parameters many times, whereby a large structure can be tested using a small set of sensors.
- The excitation can be applied to various points of the structure, not only to the roadway or the railway track. It can be helpful in the testing of secondary structural components and their local modes of vibration.
- In comparison with wind excitation, the use of an exciter is more independent of the weather and the strength of the wind (which is often too weak to adequately excite a bridge structure).

In CMA, thanks to the fact that stable excitation can be maintained for a long time, longer time series can be recorded and a much higher spectrum resolution can be obtained. In OMA, when lorries or trains are used, the resolution strongly depends on the structure's damping ratios since the recorded time series should not contain a response during a vehicle crossing or a too long section with noise after the vibrations have completely damped out (the usable data should contain only the free vibrations of the structure after the crossing). In OMA, numerous repetitions of signal acquisition at continuous excitation (e.g. by wind) are used to reduce noise in the spectra.

The weight of the exciter is usually low in comparison with the mass of the tested structure and so it has no influence on the results of the modal analysis. However, in the case of large structures, the excitation force generated by the exciter may be too weak to properly excite the structure and then the OMA methods can be helpful. The vehicle mass/structure mass ratio and the structure damping ratios are more favourable in the case of large structures, whereby the results of OMA are more precise.

Some applications of modal analysis results require the knowledge of the structure's mass-scaled mode shapes. The latter can be identified only by the CMA methods for known excitation forces.

It appears from the above that the testing methods based on CMA yield more precise results for medium and short-span structures with medium to high damping (which are difficult to excite by wind) than the OMA methods do. The preliminary test results have demonstrated the usefulness of the presented equipment and procedures for the Forced Vibration Testing of road and railway bridges and footbridges. Thanks to the proposed methodology one can precisely determine the modal parameters of bridge structures. The portable force-generating system is integrated with measuring and data acquisition equipment and it can be used for the inexpensive dynamic testing of bridges. The experimentally determined parameters can also be used to calibrate theoretical dynamic models of bridges. The proposed method can be used as a standard bridge proof-load test and as an objective tool for bridge condition monitoring in Bridge Management Systems. Further research in this field should focus on:

- improving the testing procedures in order to reduce test session time with no loss of precision;
- improving the identification procedures used to estimate modal properties from frequency response functions in order to achieve their higher precision and reliability.

References

Alampalli, S. 2000. Effects of Testing, Analysis, Damage, and Environment on Modal Parameters, *Mechanical Systems and Signal Processing* 14(1): 63–74. doi:10.1006/mssp.1999.1271

Bień, J. 2010. *Uszkodzenia i diagnostyka obiektów mostowych*. Warsaw: Wydawnictwa Komunikacji i Łączności. 417 p.

Bień, J.; Krzyżanowski, J.; Rawa, P.; Zwolski, J. 2004. Dynamic Load Tests in Bridge Management, *Archives of Civil and Mechanical Engineering* 4(2): 63–78.

Bień, J.; Rawa, P.; Zwolski, J.; Krzyżanowski, J.; Skoczyński, W.; Szymkowski, J. 2006. System for monitoring of steel railway bridges based on forced vibration tests, in *Proc. of the Conference on Bridge Maintenance, Safety, Management, Life-cycle Performance and Cost, IABMAS,* Ed. by P. J. S. Cruz, D. M. Frangopol, L. C. Neves *et al.* Porto, Portugal, 16–19 July, 2006. London: Taylor and Francis, 853–854.

Brincker, R.; Ventura, C. E.; Andersen, P. 2003. Why Output-Only Modal Testing is a Desirable Tool for a Wide Range of Practical Applications, in *Proc. of the 21st International Modal Analysis Conference on Structural Dynamics*, Kissimmee, Florida, USA, 141–145.

Bryja, D. 2009. Stochastic response analysis of suspension bridge under gusty wind with time-dependent mean velocity, *Archives of Civil and Mechanical Engineering* 9(2): 15–38.

Cunha, Á; Caetano, E.; Magalhães, F. 2007. Output-only dynamic testing of bridges and special structures, *Structural Concrete* 8(2): 67–85. doi:10.1680/stco.2007.8.2.67

Doebling, S. W.; Farrar, C. R.; Prime, M. B.; Shevitz, D. W. 1996. *Damage Identification and Health Monitoring of Structural and Mechanical Systems from Changes in Their Vibration Characteristics: A Literature Review*, Los Alamos National Laboratory, LA-13070-MS, 213 (Pt 10): 1762–1770.

Ewins, D. J. 2000. *Modal Testing: Theory, Practice and Application*. Baldock, Hertfordshire: Research Studies Press Ltd. 400 p.

Gładysz, M.; Śniady, P. 2009. Response spectrum of the bridge beam with uncertain parameters under a random train of moving forces, *Archives of Civil and Mechanical Engineering* 9(3): 31–47.

Guideline for Monitoring of Railway Bridges. Integrated Project *Sustainable Bridges: Assessment for Future Traffic Demands and Longer Lives*, 6th Framework Programme of EU [cited May 10, 2008]. Available from Internet: <http://www.sustainablebridges.net>.

Hawryszków, P. 2009. *Analiza cech dynamicznych kładek dla pieszych, ocena wrażliwości dynamicznej oraz komfortu użytkowania*. PhD thesis. Wrocław: Wrocław University of Technology.

Maia, N. M. M.; Silva, J. M. M.; Almas, E. A. M.; Sampaio, R. P. C. 2003. Damage Detection in Structures: From Mode Shape to Frequency Response Function Methods, *Mechanical Systems and Signal Processing* 17(3): 489–498. doi:10.1006/mssp.2002.1506

Olofsson, J.; Elfgren, L.; Bell, B.; Paulsson, B.; Niederleithinger, E.; Sandager, J.; Feltrin, G.; Taljsten, B.; Cremona, C.; Kiviluoma, R.; Bien, J. 2005. Assessment of European Railway Bridges for Future Traffic Demands and Longer Lives – EC Project "Sustainable Bridges", *Structure and Infrastructure Engineering* 1(2): 93–100. doi:10.1080/15732470412331289396

Skoczyński, W.; Krzyżanowski, J.; Bień, J. 2006. New Solutions of Shaker's Supporting Structure Intended to Railway Bridge Testing, in *DAAAM International Scientific Book 2006*, Chapter 46, DAAAM International, Vienna, Austria, 569–582. doi:10.2507/daaam.scibook.2006.46

Skoczyński, W.; Roszkowski, A.; Zwolski, J.; Rawa, P.; Bień, J. 2009. Usability of impact exciter for tests of civil engineering structures, in *Proc. of the 3rd International Conference "Experimental Vibration Analysis for Civil Engineering Structures – EVACES'09"*. Ed. by J. Bień. Wroclaw, Poland, 14–16 October, 2009. Wrocław: DWE, 227–235.

Wenzel, H.; Pichler, D. 2005. *Ambient Vibration Monitoring*. John Wiley & Sons Ltd. 308 p. doi:10.1002/0470024577

Zwolski, J. 2007. *Wyznaczanie cech dynamicznych konstrukcji mostowych za pomocą wzbudników drgań*. PhD thesis. Wrocław: Wrocław University of Technology.

TILTO KONSTRUKCIJŲ MODALINĖ ANALIZĖ TAIKANT PRIVERSTINĖS VIBRACIJOS TESTUS

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Santrauka

Naujų šiuolaikinių tiltų ir senesnių konstrukcijų, kurias veikia greitesnio nusidėvėjimo procesai, būklę reikia nuolat stebėti. Pagrindinės priemonės, taikomos tilto būklei vertinti, pagrįstos tilto konstrukcijų eksperimentinės modalinės analizės rezultatais. Šiame straipsnyje pagrindinis dėmesys skiriamas priverstinės vibracijos testams (angl. *Forced Vibration Tests*), atliktiems naudojant mechaninio žadinimo generatorius. Pristatoma išsami bandymo sistema, pavadinta MANABRIS, kuri buvo sukurta Vroclavo technologijos universitete. Sistemoje yra sukamasis ekscentriškas masės sužadintuvas ir programinė įranga, skirta testams programuoti ir kontroliuoti, norint gauti ir apdoroti matavimų duomenis. Priverstinės vibracijos testo (angl. *Forced Vibration Test*), atlikto su įprastu geležinkelio tiltu, rezultatai lyginami su tradicinio modalinio testo rezultatais, gautais konstrukcijas veikiant traukiniais. Vertinamas testo tikslumas ir siūlomi jo efektyvaus pritaikymo būdai.

Reikšminiai žodžiai: tiltas, dinamika, modalinė analizė, sužadintuvas, vibracijos testas, lauko testas.

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