Dynamic Tests in Bridge Monitoring – Systematics and Applications

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ABSTRACT

The purpose of this paper is classification of various dynamic tests applied in bridge monitoring. The main criterion of this systematics is the method of structure excitation. In addition the required testing equipment, data processing procedures, analyzed dynamic parameters of the structure and possible applications of the results are taken into account. Presented technologies of the bridge dynamic tests are illustrated by examples of practical applications. Special attention is paid to the usefulness of the testing procedures in the monitoring process of various types of bridge structures. Due to the fact that the monitoring is mostly focused on damage detection based on modal parameters, high precision of monitoring results is required and the issue is discussed concerning the testing techniques.

1. INTRODUCTION

Transportation network of each developed country is one of the most exploited and lively system. Bridges are the most crucial points in this network and due to their peculiar structure and extensive use they are exposed to accelerated deterioration. Many governments and local authorities as well as research institutions all over the world develop systems for planned and reasonable bridge maintenance. Bridge testing and monitoring in systematical process of maintenance build the still growing knowledge base for a short-term structure condition assessment as well as for life-cycle forecasting and budget planning.

Bridge monitoring systems require reliable data as a base for their effective operation and their usefulness in the process of structure condition assessment. Lack of the data or data buried in noise makes each, even the most sophisticated, system ineffective. In bridge monitoring systems data are collected either by permanently installed measuring systems or by systematically performed tests. The both techniques should be carefully designed taking into account the following parameters:

- the aim of the monitoring as well as size and importance of the monitored structure,
- budgeted expenses (materials, devices, traveling to the site, service costs of the installed system etc.),
- available testing equipment: sensors, DAQ systems, exciting devices (if needed), software used to data acquisition and processing,
- logistic issues (transportation, power sources, vandal and damage protection, insurance etc.),
- expected period of operation of the monitoring system, measured quantities and required precision,
- location of measuring points,
- volume of data gathered in the monitoring period, policy and format of stored and shared data.

The list doesn’t cover all issues related to the design of a monitoring system but can give an imagination of the scale of the venture which is expected to ensure reliable data.

Bridges, as other civil engineering structures like towers, chimneys and dams are continuously exposed to various dynamic loads, e.g. moving live loads, time varying wind loads, ground vibrations etc. Modern trends forcing engineers to design and build more and more brave and slender structures cause appearance of new phenomena in bridge behavior (for example see [1]). These factors stimulate still growing interest of dynamic testing in bridge engineering and development of new tools for data processing, analyses end evaluation.
Many testing methods and algorithms in bridge engineering have been borrowed from mechanical engineering where dynamic phenomena and experimental modal analysis were researched earlier. However, direct use of all these methods to bridge structures encounter many problems related to more complex nature of bridge materials like concrete, stone, brick, soil or composite materials. The investigated modal parameters of the bridge structures are also affected by ambient conditions like temperature and humidity what was reported by many teams, e.g. [2] and [3].

Choice of appropriate testing method in terms of its applicability to bridge monitoring system should be based on analysis of available techniques. Proposed taxonomy of the most popular dynamic tests of bridge structures is presented in fig. 1. Pros and cons of the selected testing methods as well as range of their application in bridge monitoring are described in the further part of this paper and illustrated by examples of a practical use.

Fig. 1. Taxonomy of the dynamic tests applied in bridge monitoring

2. AMBIENT VIBRATION TESTS

excitation forces used during ambient vibration tests are in their nature immeasurable. As a consequence the methods of data analysis developed typically for forced vibration tests and based upon Frequency Response Functions (FRF) have to be used with modifications. Instead of FRF matrix the Cross Spectrum Matrix is used to perform modal properties estimation and as a result unscaled mode shapes or operational deflection shapes are obtained together with natural frequencies and damping factors. The most important issues concerning this type of test are as follows:

- vehicles used as a source of vibration excitation affect the modal properties of the tested structure by their moving additional mass,
- the moving live load acts mainly in vertical direction; in case of existence an important horizontal mode this kind of excitation can be insufficient,
- reasonable resolution in the frequency domain is difficult to obtain because of short time of bridge excitation,
- recording of long time series of data to increase resolution of the data in frequency domain can diminish the content of valuable signal in comparison with noise by low intensity of traffic,
- location of vehicles on the bridge is limited to the roadway and some parts of the structure cannot be excited up to appropriate level,
- investigation of dynamic amplification factor (DAF) for bridges is very often influenced by properties of the vehicles suspension system and their technical condition [4].
In Poland ambient vibration tests with special vehicles are mostly performed as a part of proof load tests of new or rehabilitated bridges. Usually the main aim of this test is to assess DAF at various speeds of vehicles and to find a few first natural frequencies as well as the corresponding damping factors. During these tests accelerations, strains and/or displacements of the structure are measured to enable the DAF estimation defined as a proportion of the maximum dynamic deflection in the middle of the analyzed span to the static deflection.

The best practice in this type of test has the goal to ensure repeatability of the excitation what is important in the DAF estimation. The experiment with the trucks of known weight, passing the bridge with constant velocity and keeping the marked path on the roadway should be repeated with a few trucks of the same type. Drivers are instructed to keep the prescribed speed driving with the same gear to avoid arising undesired impulses. DAF values obtained from the tests at the same speed are usually averaged and for the assumed range of speeds a chart is created presenting the DAF function of trucks speed. The similar procedure is applied during the tests of railway bridges. This technique can serve as an additional tool in the bridge monitoring. Some conclusions concerning the bridge condition can be drawn in case the remarkable changes in character of the DAF (speed) functions during two consecutive test sessions.

Damped natural frequencies and damping ratios of the system can be estimated using the part of records acquired after the load has passed the bridge. From one stand point usage of this part of the record prevents from the effect of the additional mass loading the bridge and from the other stand point the short time remained since the vehicle passed the bridge to the signal reached the noise level results in low resolution of functions processed in frequency domain. In the tests of bridge with high damping it can make the modal properties estimation completely impossible.

Examples of the results obtained by means of special vehicles in the ambient vibration tests are shown in fig. 2. The tested highway overpass (fig. 2a) is a simple, typical structure made of reinforced concrete. The tests were carried out during a common proof load test after completing the static test. As excitation one truck was used with total weight of 400 kN passing the bridge with speed 5, 10 and 30 km/h. The structure response was measured by four accelerometers (A00 - A03) located as it is shown in fig 2b. All obtained autospectra (AS) for the sensor A01 (fig. 2c) for whole record and for the part of the record after the truck has passed the bridge were averaged and normalized to make the comparison more clear. Despite of the averaging the both spectra are noisy, however, it is visible that the peaks of the both spectra are shifted what shows the effect of bridge loading with an additional mass. Confirmation of this hypothesis can be found in the absolute values of FRF for the same location of sensor obtained in a forced vibration test (for details see chapter 3).

Generally the ambient vibration tests can be used to determine the operational parameters (see fig. 1) of the tested structure. However, this type of test can also be used for preliminary estimation of damped natural frequencies and damping factors. The test with passing special vehicles can be applied for rather large objects for which the mass of the moving load can be neglected. As it was found by many teams, e.g. [5] and [6], the application of experimental modal analysis in damage detection and monitoring should be based on higher precision tests due to small (usually a few percent) damage influence on the natural frequency shift.

3. FORCED VIBRATION TEST

Experimental modal analysis applied to bridge structure requires an appropriate excitation method to make all investigated modes observable. Heavy and stiff structures such as reinforced concrete bridges, with high damping are often difficult to properly excite either by normal traffic or even by special heavy trucks. Engineers involved in bridge testing since 70' of the last century have used special exciters for this purpose. The exciters are based on various principles of work and they generate the exciting force in different ranges of frequency. Some of them are based on principle of an unbalanced rotational mass and generate vertical or horizontal force with amplitude growing exponentially with excitation frequency. There are also devices which produce single impulses or a series of impulses with controlled frequency of repetition as well as the electro-dynamic shakers producing various types of exciting signal (sine, random, quasi-random etc.).

Application of the exciter in the modal test requires the excitation force measuring what is rather typical basic function of the device and not an additional facility. Mass of this kind of device is usually small in comparison with the mass of the tested structure and efficiency as well as precision of excitation force generation is higher than other sources of excitation. Application of exciters in the modal testing has following additional advantages:
Fig. 2. Results of the ambient vibration test with the passing trucks: a) general view of the viaduct, b) test setup (top view), c) averaged normalized autospectrum for the sensor A01 for entire record (A) and for the part of the record after the truck has passed the bridge (B) as well as the absolute values of FRF (C)
• full control of exciting force amplitude and frequency,
• excitation can be placed in various locations on the tested structure,
• possibility of keeping the constant parameters of excitation (i.e. exciting force, location, excitation frequency) even for a long time,
• possibility of structure linearity investigation by application of stepped sine excitation at different force levels,
• the best signal-to-noise ratio in case of applying the sine excitation,
• repeatability of the excitation parameters even after a long time.

Application of excitors has also a few drawbacks in comparison with other methods:
• exciter needs testing of its behavior in various ranges of excitation frequency and in various conditions of work before its practical application,
• control of the exciter requires a special computer application integrated with the software used for the data acquisition system,
• technical parameters of each exciting device limit the range of the excitation frequency in real applications and at low frequencies the excitation force can be too small.

A comprehensive system of bridge monitoring based on forced vibration tests since 2000 is being developed at Wroclaw University of Technology [7]. The general principle of this system is based on following the modal parameters of the structure identified during consecutive testing sessions. The assumed procedure of bridge monitoring starts from an initial test which has a main goal to establish a base for further investigation in form of a set of the bridge modal properties. The next test sessions, performed after a certain period of time, are focused on following changes of the previously identified modal parameters. For each monitored structure some conclusions are drawn regarding its condition on base of the observed fluctuations or changes of the modal parameters. In each test session the algorithm of testing starts from determination of FRF matrix for the selected DOFs using the stepped-sine test. The investigation results with the system damped natural frequencies and damping factors, estimated by the half power bandwidth method (HPBM). Secondly the exciter is used to excite the selected single modes with the known frequencies and a kind of impulse test is performed by switching the exciter off. Processing the recorded damped vibrations enables identification of the damping factors using the logarithmic decrement technique (LDT). The damping estimates from the both methods (HPBM and LDT) are compared to ensure reliability of the measured data. Lastly mode shapes related to the determined natural frequencies are identified at stable excitation of single mode.

Application of the forced vibration test in the bridge monitoring system for the highway overpass presented in chapter 2 is shown in fig. 3. An eccentric mass exciter (fig. 3a) was applied to induce stable vibrations in the stepped-sine test. The excitation force was measured by 3 load cells (fig. 3b) located under the exciter and the force signal used to analysis was a sum of the three signals. Technical parameters of this device enable the exciting force generation in range 3–30 Hz and the digital inverter used to control the exciter had resolution of 0.008 Hz. The exciter was placed in point No. 16 of the measuring grid and during the stepped-sine test 4 accelerometers were placed according to fig. 2b. The investigation of the resonances was carried out in range 3–12 Hz and 4 modes were found within this range (fig. 3c). The identification of the natural frequencies and damping was performed using the simple SDOF Circle Fit method (fig. 3d). The identification of each mode shape was done in a separate test at constant excitation parameters with two reference sensors (in point No. 16 and No. 35) and with two moved sensors along lines A and B (fig. 2b). Examples of the identified mode shapes are presented in fig. 3e and 3f.

The entire test was performed at stable weather conditions during about 5 hours. The length of time recording during FRF determination was 60 sec. what allows for 0.016 Hz of FRF resolution. The test was performed fully automatically by means of the software MANABRIS which controlled both DAQ system and the exciter. The same software was employed to preprocess the acquired data and present the preliminary results in form of FRF charts.

Comparison of results obtained by means of ambient vibration test and forced vibration test for the same highway overpass is presented in table 1. The values of four natural frequencies identified in ambient vibration test based on data acquired during the truck passage and after passage are compared with the corresponding results of the forced vibration test. Observed difference in values of the first natural frequency can be explained by the existence of additional mass of the moving truck and high level of noise present in the data acquired during
Fig. 3. Forced vibration test performed on the overpass shown in fig. 2a: a) the exciter used to induce vibrations, b) the load cell supporting the exciter, c) FRF’s obtained in the stepped-sine test (for the location of accelerometers see fig. 2b), d) the 3rd mode parameters identification by Circle Fit method application, e) the 3rd mode shape (8.392 Hz), f) the 4th mode shape (10.133 Hz)
Table 1. Comparison of the results of ambient and forced vibration tests

<table>
<thead>
<tr>
<th>Mode No.</th>
<th>Natural frequencies [Hz]</th>
<th>Ambient tests</th>
<th>Forced test</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>during the truck passage</td>
<td>after the truck passage</td>
</tr>
<tr>
<td>1</td>
<td>4.854</td>
<td>5.169</td>
<td>5.217</td>
</tr>
<tr>
<td>2</td>
<td>6.564</td>
<td>6.470</td>
<td>6.417</td>
</tr>
<tr>
<td>3</td>
<td>8.336</td>
<td>8.331</td>
<td>8.392</td>
</tr>
<tr>
<td>4</td>
<td>10.136</td>
<td>-</td>
<td>10.133</td>
</tr>
</tbody>
</table>

ambient test. The 4th vibration mode couldn’t be identified in the data acquired after the truck passage due to weak excitation of this mode during passage and relatively high damping of this mode.

The tests results are promising in terms of application in bridge monitoring. The monitoring system being developed by the team from WUT can be used for road and railway bridges as well as for footbridges, especially for steel structures. Current research is being done in field of use the forced vibration tests results for damage detection. The system is dedicated to identify structure damages such as cracks or connector loosening and actually the sensitivity of the system is being tested. The effect of ambient conditions influence on modal properties of the structures is also investigated in scope of this work.

4. FREE VIBRATION TEST

Free vibration tests are widely used in bridge monitoring due to fact of simple inducing vibration by a single impulse produced by impact hammer, dropping weight, suddenly releasing applied deflection etc. This method is especially effective in application to flexible structures with low damping when the usable signal can be acquired for long time what means the higher resolution in frequency domain. Free vibration test has the same advantages as forced test and its results can be processed in a similar way when the impulse force is measured. The difference is only in repeatability of the excitation. One of the most important sources of scatter in results of free vibration test is the way of excitation force application (e.g. deviation from the axis perpendicular to the hit surface in test with the impact hammer). The second issue can be the signal to noise ratio. On one hand excitation of a large structure by force impulse is difficult for the sake of so called crest effect and on the other hand the ambient noise at the site is sometimes too high (e.g. a bridge over deep valley with strong wind, neighborhood of busy street or railway line etc.) to perform the test with properly induced vibrations. The first obstacle can be avoided by usage of excitation in form of releasing the applied deflection what can have more energy than the force impulse and it doesn’t cause local damages. Applications of stochastic methods of data processing and modal properties identification with white noise modeling can solve the second problem.

The free vibration test are often used in cable force monitoring of the existing bridge. It is one of the most useful methods of force identification in tendons after their installation. The force determination is performed indirectly by identification of cable natural damped frequency with its harmonics and calculation the force taking into account the cable length, weight, and material properties.

Application of the free vibration test in gathering valuable data for bridge monitoring is illustrated by example of Millennium Bridge in Wroclaw, Poland. It is a cable stayed bridge (fig. 4a) and during the common static proof load test the forces in the selected cables (fig. 4b) were monitored by the vibration method. Measured accelerations were used for estimation of the cables’ natural frequencies and damping. For the force calculation the formulas given in [8] were applied. To assess the influence of sag effect and the bending stiffness of the cable on the cable force the following three parameters were calculated:

\[ \lambda^2 = \left( \frac{mgl}{H} \right)^2 \frac{EAL}{HL_e} \]  

\[ \xi = L \frac{T}{EI} \]
Fig. 4. Tests of the main part of Millennium Bridge in Wroclaw, Poland: a) general view of the bridge, b) setup of the test with location of the static loading and accelerometers on the selected cables (side view), c) proof load scheme S1 (top view), d) proof load scheme S2 (top view), e) forces in the cable 4.6 estimated in the 14 consecutive levels of the bridge static proof load test.
\[ L_c = L \left( 1 + \frac{1}{8} \left( \frac{mgL}{H} \right)^2 \right) \]  

where \( L \) – cable length [m], \( m \) – mass of 1 m of cable [kg/m], \( g = 9.81 \text{ m/s}^2 \), \( H \) – chord force [N], \( T \) – axial force [N], \( E \) – cable elasticity modulus [Pa], \( A \) – cross-section area [m²], \( I \) – bending moment of inertia [m⁴]. According to [8] authors’ recommendation \( T = H \) was assumed for cables with a small sag (smaller than 1:8). Approximate force value from the taut string formulae:

\[ T = 4mL^2 f^2 \]  

where \( f \) is the first natural frequency of the cable [Hz]. Small values of \( \lambda^2 \) (\( \lambda^2 < 0.17 \)) and medium values of \( \xi \) (\( 18 < \xi < 210 \)) were obtained for the analyzed cables what, according to [8], means that in the force calculation the sag effect can be neglected and the bending stiffness of the cable should be taken into account and finally the formula (5) was used:

\[ T = m \left( 2Lf - \frac{2.363}{L} \sqrt{\frac{EI}{m}} \right)^2 \]  

The obtained calculated forces in one selected cable (4.6) during consecutive stages of static proof load test of the bridge are presented in fig. 4e. The presented forces include the initial tension force and is also produced by the dead load of the span and the live load. The presented results confirm sensitivity of the applied method to the relatively small changes of the cable force caused by various levels of proof load what is of great importance for monitoring purposes.

Generally the test is simple to perform and it doesn’t need any special device to induce vibration. However, the mentioned difficulties in performing the test in the real environment cause that for modal analysis with high precision the free vibration tests are used mainly for steel or steel-concrete composite bridges with flexible decks.

5. CONCLUSIONS

The three presented techniques of dynamic testing are widely used in bridge engineering and great library of reports and papers is available presenting the experiences of these applications. This paper is focused on potential possibility of modal tests application to bridge monitoring. In the presented example of the highway overpass tests the forced vibration test seems to be better choice than ambient test for the sake of the structure high damping and better signal-to-noise ratio. The identified modes of the viaduct’s superstructure were well separated in frequency domain what enables application of the Circle Fit estimation method.

The bridge monitoring system developed by WUT based on forced vibration tests is being under construction and calibration however, it was successfully examined during field tests [7]. The system confirmed also usefulness in monitoring of progressive damages of real bridge structure [9].

The selection of the best method of structure excitation and data processing method fitting the specific task is sometimes confusing. Awareness of all advantages and drawbacks of the testing technique helps to make the proper choice and allows avoiding mistakes in data processing. Effective application of the presented techniques depends also on the available equipment, software and experience in its usage.

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